Hydrochemistry of Aquifer Systems and Relation to Regional Flow Patterns in Cretaceous and Older Rocks Underlying Kansas, Nebraska, and Parts of Arkansas, Colorado, Missouri, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 94–4144





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By C.H. BAKER, JR., and R.B. LEONARD

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CONVERSION FACTORS AND VERTICAL DATUM

Ву	To obtain	
0.3048	meter	
25.4	millimeter	
1.609	kilometer	
2.590	square kilometer	
	0.3048 25.4 1.609	0.3048 meter 25.4 millimeter 1.609 kilometer

Temperature can be converted to degrees Celsius (°C) or degrees Fahrenheit (°F) by the equations:

$$^{\circ}C = 5/9 (^{\circ}F - 32)$$

$$^{\circ}F = 9/5 (^{\circ}C) + 32.$$

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

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Abstract

Six major geohydrologic systems are recognized in the Precambrian- to Cretaceousage rocks underlying the study area of the Central Midwest regional aquifer-system analysis. On the basis of both ground-water flow patterns and hydrochemistry, the study area is divided into two subregions—the Plains subregion in the north and west and the smaller Ozark subregion in the southeast.

The basement confining unit, in Precambrian crystalline rocks, underlies the entire study area and retards the downward movement of ground water. This unit yields little water, and the hydrochemistry is not discussed in this report.

In the Plains subregion, the Western Interior Plains aquifer system directly overlies the basement confining unit. The aquifer system is divided into two aquifer units separated by a thin confining unit. Water in the Western Interior Plains aquifer system is confined by a great thickness of slightly permeable rocks called the Western Interior Plains confining system. This confining system is overlain in the northwestern one-half of the Plains subregion by the Great Plains aquifer system, which consists of two aquifer units and a thin, discontinuous confining unit. Overlying the Great Plains aquifer system throughout most of the area, the Great Plains confining system restricts the exchange of water between the

aquifer system and the shallow unconfined aquifers.

In the Ozark subregion, in general, the same geologic formations that contain the Western Interior Plains aquifer system comprise the Ozark Plateaus aquifer system.

Although the rock units are laterally continuous between the Plains and Ozark subregions, differences in both ground-water flow patterns and water chemistry warrant the separation into different aquifer systems. The Ozark Plateaus aquifer system consists of three aquifer units and two confining units.

Rocks of the Western Interior Plains aquifer system are deeply buried, and permeability is very small. Water appears to move radially outward from a geopressure zone in the Anadarko Basin of Oklahoma and Texas and generally east and southeast elsewhere. Large concentrations of dissolved solids predominate throughout the aquifer system, and most of the water is a sodium chloride type. Ion ratios suggest that the water in the Western Interior Plains aquifer system was derived from seawater by concentration and by depletion of calcium and sulfate ions.

Although the Western Interior Plains confining system functions as a regional confining unit, extensive units of sandstone and limestone in the lower part of the section are permeable and function as aquifers and locally as petroleum reservoirs. Ground water in the permeable parts of the system moves primarily eastward across the Plains subregion. Most of

the water has large concentrations of dissolved solids and is a sodium chloride type. Both concentrations of depositional seawater and dissolution of the extensive evaporite deposits in the upper part of the confining system have contributed to the observed chemical character of the water.

Flow of ground water through the Great Plains aquifer system in the study area is predominately from west to east. Water types are more variable than in the Western Interior Plains aquifer and confining systems. Calcium bicarbonate water near the western outcrop areas probably results from dissolution of carbonate cement by meteoric water entering the aquifer. The relatively large concentrations of dissolved solids in sodium chloride water in the deeper parts of the aquifer system reflect concentration of the brackish water in which the rocks were deposited. Locally large concentrations of calcium, sodium, sulfate, or chloride result from dissolution of underlying evaporite deposits.

In the southeastern two-thirds of the study area, where the Great Plains aquifer system is absent, older rocks are at or near land surface and have been subjected to erosion and subaerial weathering. The hydraulic properties of the rocks have been altered by these processes, and the chemical composition of the water has been affected by the admixture of meteoric water.

Regional ground-water movement in the Ozark Plateaus aquifer system is radially outward from a topographic high near the center of the Ozark subregion. Part of each aquifer unit is exposed at the land surface, and fresh meteoric water moves primarily through fractures and solution openings in the predominately carbonate rocks. Consequently, virtually all connate water has been flushed out of the system, and the dominant water chemistry is the result of dissolution by meteoric water. Concentrations of dissolved solids are small, and the ions are principally calcium, magnesium, and bicarbonate.

In the Plains subregion, water from depths of less than 500 feet bears little resemblance to that from greater depths. Water from depths of less than 500 feet varies greatly in dissolved-solids concentration and water type. Composition of the rocks in the Plains subregion is a major factor affecting water chemistry, complicated by the presence of beds and lenses of evaporite and by upward leakage through thin confining layers. The principal aquifers in the Ozark subregion, however, are at or near land surface, and little chemical distinction can be made between water from deep and shallow sources.

INTRODUCTION

The study area for the Central Midwest regional aquifer-system analysis (Central Midwest RASA) includes about 370,000 square miles near the geographic center of the conterminous United States (fig. 1). It extends from the foothills of the Rocky Mountains in Colorado to the Missouri and Mississippi Rivers in eastern Nebraska and Missouri, and from South Dakota to the Ouachita, Arbuckle, and Wichita Mountains of Arkansas and Oklahoma. Within this broad region, six major geohydrologic systems have been identified. Five of these regional systems are considered by the Central Midwest RASA; the sixth, the High Plains aquifer, has been the subject of a separate study. Four neighboring RASA studies, which in places share geographic or hydrologic boundaries with the present study, have been made—the High Plains RASA (Weeks and others, 1988), the Northern Great Plains RASA (Downey and Dinwiddie, 1988), the Northern Midwest RASA (Young, 1992), and the Gulf Coast RASA (Grubb, 1992). The areal extent of these RASA studies is shown in figure 2. The background, purpose, scope, objectives, and approach of the Central Midwest RASA study are described in the plan-of-study report prepared by Jorgensen and Signor (1981).

Purpose and Scope

The purpose of this report is to describe the chemical character of the water contained in the

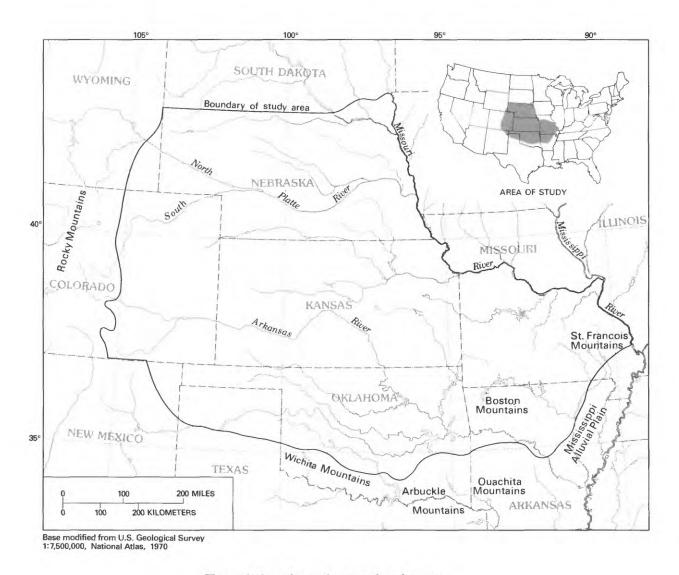


Figure 1. Location and extent of study area.

regional geohydrologic systems and to discuss, to the extent possible, the causes for the hydrochemical variability and relations to regional flow patterns. Although a major part of the High Plains aquifer is included in the study area, that aquifer is described elsewhere and is specifically excluded from the Central Midwest RASA, which deals only with aquifers in rocks of Cretaceous age and older.

Plans for the Central Midwest RASA did not include the collection and analysis of water samples; this study is based on chemical data that were available from various sources in 1983. The hydrochemical conclusions in this report are based

primarily on the distribution of solute concentrations and on ratios of common ions, which are particularly useful for comparing the present chemical character of the water with that of hypothetical sources.

More detailed studies, including geochemical models and detailed analysis of the distribution of the less-common elements, such as bromine, iodine, iron, manganese, and others, are necessary for a more comprehensive understanding of the origins and evolution of water in these deeply buried aquifers. The hypotheses suggested here are plausible in the context of currently available data,

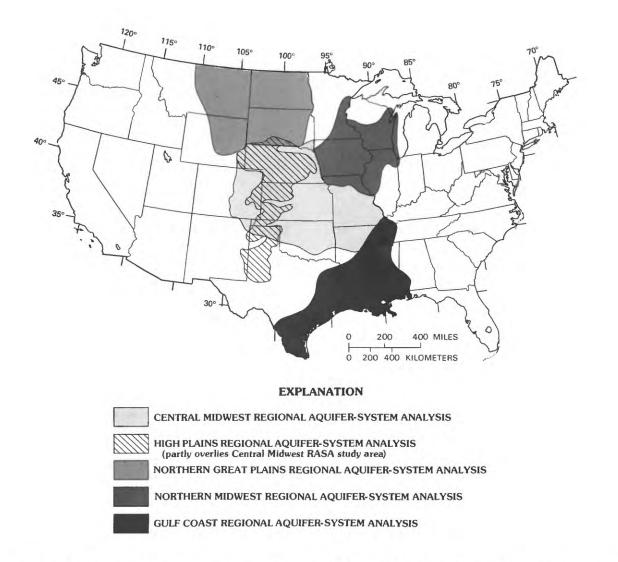


Figure 2. Regional aquifer-system analyses contiguous to the Central Midwest regional aquifer-system analysis.

and all may not stand the test of more detailed study; they are offered here primarily as a stimulus to further study.

Acknowledgments

The authors are indebted to many people for assistance in compiling the data on which this report is based. State agencies in the study area furnished useful unpublished data.

D.O. Whittemore and P.A. Macfarlane of the Kansas Geological Survey (Lawrence) provided

fruitful discussions and suggestions. Patricia Tracy of the University of Oklahoma (Norman) made arrangements for the retrieval of hydrochemical data from the Petroleum Data System Brine File and provided the necessary descriptions of the data formats; personnel of the Nuclear Division of Union Carbide Corporation (Oakridge, Tennessee) performed the same functions for data from the National Uranium Resources Evaluation project. Finally, thanks to Don Wolfram and Fred Sherman who, as student assistants of the Central Midwest RASA, spent many hours preparing and editing the hydrochemical maps that are a part of this report

and wrote many computer programs to assist in the evaluation and analysis of the data.

GEOHYDROLOGIC FRAMEWORK

A detailed discussion of the geohydrology of the study area is included in an earlier paper prepared for the Central Midwest RASA (Jorgensen and others, 1993). The paper grouped the geologic units of the study area into three major aquifer systems and three major confining systems. The areal extent of the three aquifer systems are shown in figure 3, and stratigraphic relations of the six geohydrologic systems are depicted in figure 4 and in more detail by Jorgensen and others (1993, plate 2). The major structural features of the study area, which affect both the movement and the chemistry of the ground water, are shown in figure 5.

The geohydrologic units within the study area, except near major structural features and in other areas of complex stratigraphic relations, generally correlate with the regional stratigraphic units. A major exception is along the boundary between what are termed the "Plains" subregion and the "Ozark" subregion (fig. 3). In this area, the rocks of Mississippian age and older, although laterally continuous, contain two distinct flow systems. Freshwater in the Ozark Plateaus aquifer system flowing generally westward meets saline water that is flowing eastward in the Western Interior Plains aquifer system (fig. 4). The transition zone between these two flow systems is marked by a broad low in the potentiometric surface (fig. 6) that is nearly coincident with a broad topographic low. Water from the two flow systems mingles and moves upward to the water table and discharges to springs or streams in the topographically low area.

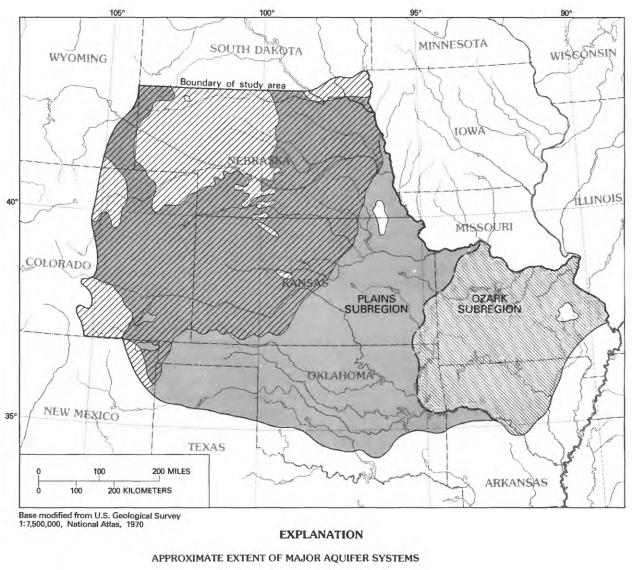
The lowermost geohydrologic unit, called the basement confining unit, is present throughout the study area. The unit is composed mostly of crystalline rocks of Precambrian age. These materials generally are not regarded as water bearing and are not discussed in the hydrochemical section of this report.

Four major regional geohydrologic units underlie the Plains subregion above the basement confining unit. These systems, from deepest to shallowest, are the Western Interior Plains aquifer system, the Western Interior Plains confining system, the Great Plains aquifer system, and the Great Plains confining system. The uppermost regional geohydrologic system in the western part of the subregion, the High Plains aquifer, is not a part of the Central Midwest RASA. A generalized correlation of these geohydrologic units with stratigraphic units is shown in table 1.

Rocks of the Western Interior Plains aquifer system consist mainly of dolostone, limestone, and shale of Late Cambrian through Mississippian age. The aquifer units in the system compose a reasonably distinct hydraulic system. At most locations, the aquifer units are permeable and water yielding except where compaction of deeply buried rocks in structural basins has greatly reduced the permeability. The quifer system is several thousand feet thick in the Anadarko and Arkoma Basins. The Western Interior Plains aguifer system underlies most of the Plains subregion at depth. The system is divided into an upper aquifer unit of permeable limestone, a thin confining unit of slightly permeable shale, and lower aquifer units of limestone, dolostone, and sandstone that directly overly the crystalline basement rocks. Because the confining unit is thin and locally discontinuous, the upper and lower aquifer units act as a single hydraulic system but exhibit somewhat different water chemistry.

The Western Interior Plains confining system restricts water flow to and from the Western Interior Plains aquifer system at nearly all locations, including the deep basins. The thick confining system consists of layered shale, limestone, sandstone, and evaporite deposits of Late Mississippian through Jurassic age. The thickness of the confining system ranges from more than 20,000 feet in the Anadarko Basin to near zero along the periphery of the Ozark Plateaus. Although these rocks represent a regional confining system, many of the rock layers are locally permeable and yield water to wells. A discussion of the hydrochemistry of these rocks is included in this report.

The Great Plains aquifer system overlies the Western Interior Plains confining system in the northern one-half of the Plains subregion. It consists of two regional aquifers and a confining unit. Both aquifers are composed predominately of slightly cemented water-bearing sandstone of Early



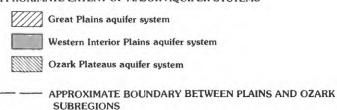


Figure 3. Extent of major aquifer systems.

Cretaceous age; they are separated at most locations by a thin shale confining unit. The rocks of the aquifer system crop out in southeastern Colorado and northeastern New Mexico and in the Black Hills of South Dakota. In these areas, the system receives some recharge from meteoric water. The rocks of the aquifer system also crop out along its eastern margin in central Kansas and

eastern Nebraska, which is generally an area of discharge.

The Apishapa aquifer, the lower of the two aquifers in the Great Plains aquifer system, is composed of permeable, loosely cemented, medium-to very fine-grained sandstone of the Cheyenne Sandstone and its equivalents. The thickness of the unit typically ranges from 100 to 200 feet, although it is absent in some locations and elsewhere attains a

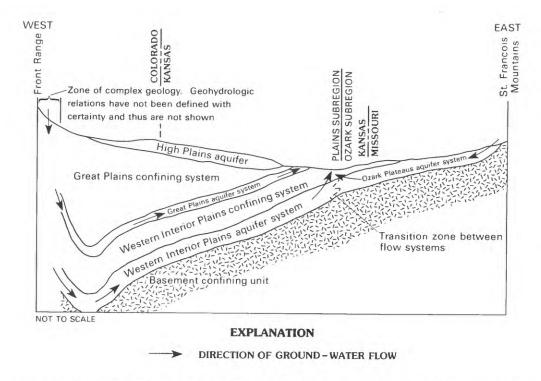


Figure 4. Major geohydrologic units in the Plains and Ozark subregions. Section extends from central Colorado to St. François Mountains in southeastern Missouri.

maximum thickness of 400 feet. The Apishapa confining unit restricts water flow between the Apishapa aquifer and the overlying Maha aquifer. The confining unit is composed mostly of very slightly permeable shale of the Kiowa Shale and equivalent formations. The unit, where it is present, is typically less than 100 feet thick.

The upper of the two aquifer units in the Great Plains aquifer system, called the Maha aquifer, is more extensive than the underlying Apishapa aquifer and Apishapa confining unit. The Maha aquifer consists mainly of water-bearing sandstone of the Dakota Sandstone and its equivalents. The unit typically is thicker than the underlying Apishapa aquifer, reaching a maximum thickness of more than 900 feet in eastern Nebraska.

The Great Plains confining system overlies the Great Plains aquifer system and restricts flow of water between that system and the High Plains aquifer or the shallow water-table aquifers. The confining system consists primarily of thick and only slightly permeable shale of Late Cretaceous age. Maximum thickness of the confining system

exceeds 8,000 feet in the Denver Basin in the western part of the area, but the confining system thins eastward and disappears near the eastern margin of the underlying aquifer system. The Great Plains confining system generally does not yield water to wells in the study area.

In the Ozark subregion, the rock units equivalent to the Western Interior Plains aquifer system in the Plains subregion comprise the Ozark Plateaus aquifer system. Although the strata are laterally continuous between the Plains and Ozark subregions, the flow patterns differ greatly and warrant the separation into different aquifer systems. The Ozark Plateaus aquifer system consists of three aquifer units separated by generally thin confining units. The general correlation of the units in the Ozark Plateaus aquifer system with stratigraphic units in the subregion is shown in table 2.

The St. Francois aquifer, the lowermost unit of the Ozark Plateaus aquifer system, lies directly on the basement confining unit in the Ozark subregion. It is composed mainly of Upper Cambrian water-bearing sandstone and dolostone. The aqui-

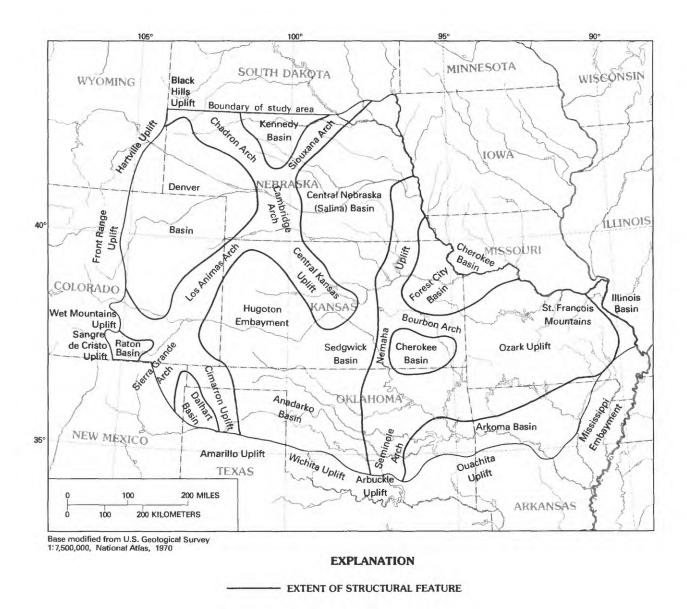
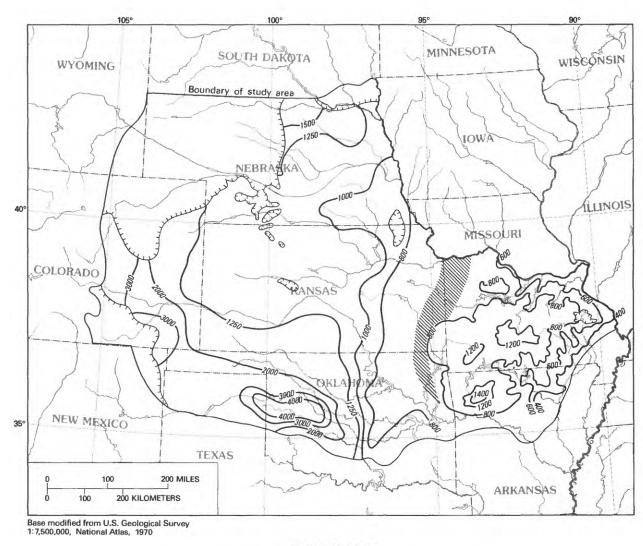


Figure 5. Major structural features (modified from Condra and Reed, 1959; Carlson, 1963; Merriam, 1963; Oetking and others, 1966, 1967; Renfro and others, 1973; Bennison and Chenoweth, 1984).

fer is more than 1,000 feet thick near the Mississippi alluvial plain (fig. 1) but is typically from 200 to 500 feet thick over most of its extent. The St. Francois confining unit, which overlies the St. Francois aquifer, consists of shale, siltstone, dolostone, and limestone of Late Cambrian age. Although the confining unit partially restricts the flow of water to and from the St. Francois aquifer, the unit is leaky.

The Ozark aquifer is the most extensive, most permeable, and most extensively used aquifer in the Ozark subregion. It consists primarily of waterbearing fractured and permeable dolostone of Late Cambrian through Middle Devonian age. The aquifer is typically about 1,000 feet thick, making it the thickest unit in the Ozark Plateaus aquifer system. Rocks of the Ozark aquifer crop out over much of the subregion, and the aquifer is generally unconfined. The Ozark confining unit locally restricts the exchange of water between the Ozark aquifer and the overlying Springfield Plateau aquifer. The confining unit is composed principally of shale of Late Devonian through Early Mississippian age.

The Springfield Plateau aquifer in the western part of the Ozark subregion consists of water-



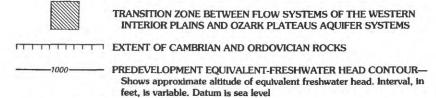


Figure 6. Predevelopment equivalent-freshwater head in Cambrian and Ordovician rocks and location of transition zone between 1.Jw systems of the Western Interior Plains and Ozark Plateaus aquifer systems (modified from Jorgensen and others, 1993).

bearing fractured and permeable Mississippian limestone. Aquifer thickness typically ranges from 100 to 400 feet but locally may exceed 1,400 feet. Slightly permeable Pennsylvanian rocks, including part of the Western Interior Plains confining system, overlie the western part of the Springfield Plateau aquifer and restrict movement of water between the aquifer and the near-surface water table.

SOURCES OF DATA AND METHODS OF ANALYSIS

Sources of Hydrochemical Data

More than 34,000 chemical analyses of water samples were compiled from the U.S. Geological Survey's National Water-Data Storage and

Table 1. Generalized correlation of geohydrologic units to stratigraphic units in most of the Plains subregion

[From Jorgensen and others, 1993]

Geohyd	lrologic unit	Principal rock-stratigraphic unit(s)	Time- stratigraphic uni
High P	lains aquifer	Ogallala Formation and unconsolidated deposits	Quaternary and Tertiary
Great Plains	confining system	Pierre Shale, Niobrara Chalk, Carlile Shale, Greenhorn Limestone, Graneros Shale	Late Cretaceous
Great	Maha aquifer	Dakota Sandstone, "D" sandstone, "J" sandstone, and equivalent of Newcastle Sandstone	
Plains aquifer	Apishapa confining unit	Skull Creek and equivalent of Kiowa Shale	Early Cretaceous
system	Apishapa aquifer	Cheyenne Sandstone and equivalent of Fall River Sandstone and Lakota Sandstone	
Ii l	Vestern nterior Plains onfining system	Morrison Formation, Sundance Formation, Entrada Sandstone, Dockum Formation, Elk City Sandstone, Doxey Shale, Big Basin Sandstone, Cloud Chief Formation, Day Creek Dolomite, Whitehorse Sandstone, Nippewalla Group, Sumner Group, Chase Group, Council Grove Group, Admire Group, Wabaunsee Group, Shawnee Group, Douglas Group, Lansing Group, Pleasanton Group, Marmaton Group, Cherokee Group, Atokan rocks, Morrowan rocks, and Springer Group	Jurassic through Late Mississippian (Chesterian)
Western	Upper aquifer unit	Meramecian, Osagean, and Kinderhookian rocks	Late
Interior	Confining unit	Chattanooga Shale and Woodford Shale	Mississippian
Plains aquifer system	Lower aquifer units	Hunton Group, Sylvan Shale, Galena Dolomite and equivalent of Viola Limestone, Simpson Group, Arbuckle Group, and Reagan Sandstone	through Late Cambrian
Basement	t confining unit	Mostly igneous and metamorphic rocks	Cambrian and Precambrian

Table 2. Generalized correlation of geohydrologic units to stratigraphic units in most of the Ozark subregion

[From Jorgensen and others, 1993]

Geohyd	rologic unit	Principal rock-stratigraphic unit(s)	Time- stratigraphic uni
	Interior Plains	Marmaton Group, Cherokee Group, Atokan rocks, Bloyd Shale, Hale Formation, Morrowan rocks, Pitkin Limestone, Fayetteville Shale, and Batesville Formation	Middle Pennsylvanian through Late Mississippian (Chesterian)
	Springfield Plateau aquifer	Moorefield Formation, St. Louis Limestone, Salem Limestone, Warsaw Limestone, Boone Formation, St. Joe Limestone Member of Boone Formation, Keokuk Limestone, Burlington Limestone, and Fern Glen Limestone	Mississippian
	Ozark confining unit Clifty Limestone, Per Lafferty Limestone Limestone, Brassfield Cason Shale, Fernvale Kimmswick Limesto Limestone, Joachim Dole Sandstone, Fyerton Forz	*Chouteau Group and Chattanooga Shale	Early Mississippian and Late Devonian
Ozark Plateaus aquifer system	Ozark aquifer	Clifty Limestone, Penters Chert, Lafferty Limestone, St. Clair Limestone, Brassfield Limestone, Cason Shale, Fernvale Limestone, Kimmswick Limestone, Plattin Limestone, Joachim Dolomite, St. Peter Sandstone, Everton Formation, Powell Dolomite, Smithville Formation, Cotter Dolomite, Jefferson City Dolomite, Gasconade Dolomite, Gunter Sandstone Member of Gasconade Dolomite, Roubidoux Formation, Eminence Dolomite, and Potosi Formation	Middle Devonian through uppermost Cambrian
	St. Francois confining unit	Elvins Group, Derby and Doe Run Dolomite, Davis Formation	Late Cambrian
	St. Francois aquifer	Bonneterre Dolomite and Lamotte Sandstone	Late Camorian
Basement	confining unit	Mostly igneous and metamorphic rocks	Precambrian

^{*}Not U.S. Geological Survey usage in Missouri, but name used by State or U.S. Geological Survey for equivalent unit in adjacent States.

Retrieval System (WATSTORE), the brine file maintained by the Kansas Geological Survey (Lawrence), the Petroleum Data System Brine File (PDS) maintained at the University of Oklahoma (Norman), and the National Uranium Resources Evaluation (NURE) project files (Oakridge, Tennessee). Additional analyses from published and unpublished sources were added as available. At the time that the data were transferred, the PDS and NURE data were largely unedited; these, as well as data from other sources, contained many apparent inconsistencies. All the results of analyses were stored in a computer file at the U.S. Geological Survey in Lawrence, Kansas (Helgesen and Hansen, 1989).

Consistency and reliability of the chemical analyses varied considerably. Data in the WATSTORE system generally are from samples collected by employees of the U.S. Geological Survey following well-established techniques for sampling water supplies. Analytical results generally are screened before being entered into the WATSTORE system, and these data are usually reliable. However, most of the samples were collected from water-supply wells or shallow test holes and, because the aquifers described in this study are usually deeply buried, only a small number of useful samples were available from WATSTORE.

Water samples described in the PDS file were collected by a large number of drilling companies and personnel for a variety of purposes. Conditions under which samples were collected, sample-collection methods, and analytical techniques varied considerably. Many samples were analyzed for only a few constituents, depending on the needs and interests of the collectors. Additionally, the location information for many samples, although adequate for the needs of those who did the sampling, were not sufficiently precise for machine plotting and evaluation. The variety of stratigraphic terms used by the collectors made it difficult to determine the geohydrologic source of many samples.

The utility and accuracy of the NURE data were variable, depending largely on the objectives and abilities of the contracted data collectors. Like the WATSTORE samples, the NURE samples were commonly from shallow aquifers and had only limited applicability to the present study.

Even though a large number of analyses were available, the areal distribution of the data presented additional problems. WATSTORE samples generally were collected as a part of studies to evaluate the ground-water resources of relatively small areas, and their distribution is very uneven. Data in the PDS file come almost entirely from exploration and production in active (or abandoned) oilfields; many samples are available from each field, but there are large areas between fields where no data are available.

Methods of Data Analysis and Presentation

For the purposes of this study, the entire data set just described was called the "working file." A subset of the working file, the "project file," was selected on the basis of the completeness and perceived accuracy of the chemical data. Finally, a subset of the project file, the "data-base" file, was selected for use in contouring the water-quality data for the maps shown in this report.

Initially, all members of the working file from each geohydrologic unit were machine plotted and posted with the concentration values or ion ratios for the ions of interest and with a unique number that served to identify the sample. Obvious anomalous values were identified manually from these plots and rejected; the remaining samples were examined for completeness and ionic balance.

The ions in a stable water sample are electrically balanced. Theoretically, in a valid, complete analysis, the sum of the concentrations of cations should equal the sum of the concentrations of anions when concentrations are expressed in milliequivalents per liter (meq/L). The "ionic balance," D%, is defined by the relation

$$D\% = |C - A| \times \frac{100}{(C + A)} , \qquad (1)$$

where C and A are the sums of the concentrations of cations and anions, respectively, in milliequivalents per liter. Water samples are seldom analyzed for all ions that are present; hence D% is generally greater than 1.0, even for valid and "complete" analyses. Values of D% less than 0.1 normally are suspect, particularly for older analyses. It was common laboratory practice before the early 1960's not to determine the concentrations of sodium and

potassium by laboratory methods. Instead, the difference between the sum of the anions and the sum of calcium and magnesium was converted to milligrams per liter of sodium and reported as "sodium plus potassium." Conversely, a large value of D% might well represent an analytically accurate partial analysis for a few selected constituents that did not include all the major ions.

In areas where abundant samples from a geohydrologic unit were available, those with values of D% greater than 10 were rejected from inclusion in the project file. In areas where data were scarce, partial analyses that included values for chloride were accepted. Chloride was chosen because it is the most conservative of the common ions and is generally present and analyzed for in oilfield brines. Some analyses that included values for dissolved solids but not for chloride were retained where data were scarce and the dissolved-solids values were in reasonable agreement with values for other analyses in the area.

Samples for the data-base file were chosen from the project file by selecting one or two samples from each 5-minute quadrangle in the study area. (Near the center of the study area, a 5-minute quadrangle covers about 26 square miles.) In quadrangles where multiple samples were available, the samples that contained the median value of chloride and dissolved solids were chosen for each geohydrologic unit. Median, rather than mean, values were chosen because the data values generally were not normally distributed in time or space. Median values tend to be affected less by extreme and anomalous values in the data sets and to more nearly reflect regional continuity than do mean values. If the quadrangle contained an even number of samples, the analysis containing the first value larger than the median was chosen, so that the selected value in each quadrangle represented an actual analysis rather than a true median.

In some quadrangles, no analyses were available from which dissolved-solids concentration could be derived, but reliable values for chloride concentration were available. Under these conditions, dissolved-solids concentration was estimated from chloride concentration by regression analysis, using chloride and dissolved-solids concentrations from surrounding quadrangles.

For large areas where no chemical data were available, concentrations of chloride and dissolved solids were estimated from measured resistivity of water data. Resistivity of formation fluid commonly is measured by the oil industry during drillstem or production tests as an aid to electric-log interpretation, and many values of measured resistivity were available from logs and published sources. For about 2,200 locations where measured resistivity data were unavailable, resistivity of the formation water was estimated from geophysical logs. About 1,900 estimates were made from spontaneous-potential logs, using techniques described in standard logging references (Schlumberger, 1972). The remaining estimates, mainly for water from carbonate rocks, were made using cross-plots of the resistivity of the rock-water medium and its porosity, as described by Jorgensen (1988). Salinity values for sodium-chloride solutions of given resistivity were calculated from standard tables (Weast and Astle, 1982) and converted to concentrations of dissolved solids using a factor of 1.04 to account for the other ions in a typical oilfield brine.

The chemical data are presented in this report on maps showing lines of equal chloride concentration, dissolved-solids concentration, and selected ion ratios (in milliequivalents per liter), and a hydrochemical facies map. These maps were prepared from data in the data-base file, supplemented by additional data from the project file, and by estimates of the concentrations of chloride and dissolved solids where no better data were available.

HYDROCHEMISTRY OF AQUIFER SYSTEMS AND RELATION TO REGIONAL FLOW PATTERNS

The Western Interior Plains aquifer system is distinguished from the Ozark Plateaus aquifer system on the basis of flow patterns; there is no lithologic discontinuity between the two aquifer systems (Jorgensen and others, 1993). The aquifer materials in both systems consist predominantly of limestone, dolostone, and dolomitic sandstone, and the permeability is mostly secondary and diagenetic in origin.

The trilinear diagram in figure 7 illustrates the change in hydrochemistry in the transition zone

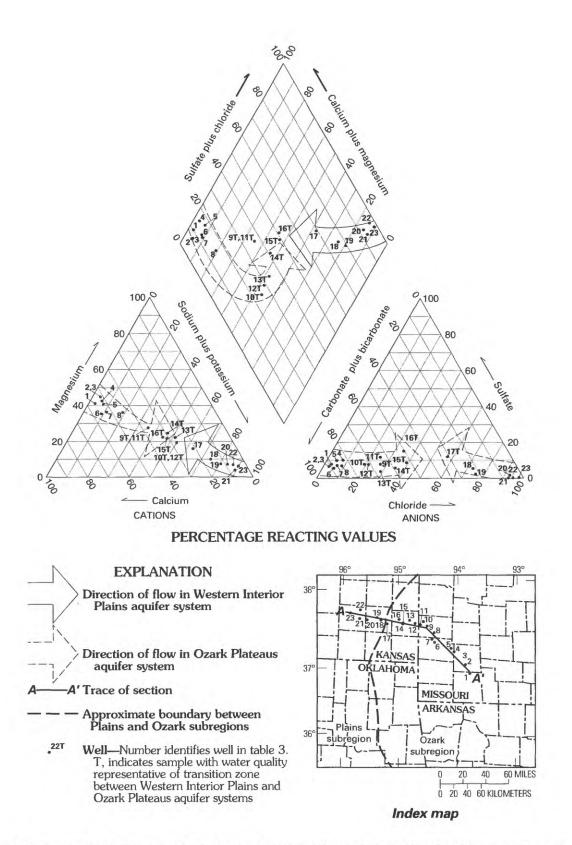


Figure 7. Changes in hydrochemistry of water from the Western Interior Plains and Ozarks Plateaus aquifer systems along section A'-A'.

(fig. 6), where water from the Western Interior Plains aquifer system mixes with water from the Ozark Plateaus aquifer system. Selected analytical data for the samples is given in table 3. The curvature of the flow path in the diamond of the trilinear diagram indicates that the dominantly calcium magnesium water (samples 1 through 8) increases in sodium and potassium with distance down the flow path (samples 9 through 16). Paleohydrologic analysis (Jorgensen, 1993) suggests that the flow in the Ozark Plateaus aquifer system is expanding through geologic time as saline water is flushed from the rocks of the Western Interior Plains aquifer system.

Calculated saturation indices for the samples are listed in table 4. In general, water from the upgradient part of the Ozark Plateaus aquifer system is undersaturated with respect to calcite and dolomite but becomes less undersaturated down the flow path (samples from well nos. 1 through 9). When mixed with water from the Western Interior Plains aquifer system, the water becomes saturated with respect to these compounds (samples from well nos. 10 through 16).

Because of the great differences in both flow patterns and water chemistry, the Western Interior Plains aquifer system and the Ozark Plateaus aquifer system are discussed separately. For convenience, however, the hydrochemical features of the two systems are illustrated together in figures 8 through 17.

Plains Subregion

Western Interior Plains Aquifer System

Rocks of the Western Interior Plains aquifer system are deeply buried beneath a thick confining system in most of the Plains subregion. Concentrations of dissolved solids are generally quite large, and the water is almost exclusively a sodium chloride brine. The system is subdivided by Jorgensen and others (1993) into an upper aquifer unit, a shale confining unit, and lower aquifer units (table 1). Although the confining unit is not everywhere present and is locally leaky, the water chemistry of the lower aquifer units differs considerably from that of the confining unit and the upper aquifer unit.

Lower Aquifer Units

The rocks of the lower aquifer units of the Western Interior Plains aquifer system are predominantly dolostone, limestone, and dolomitic sandstone, with some beds of shale and sandstone. Over most of the Plains subregion, the rocks of the lower aquifer units have not been exposed to subaerial weathering and have been compacted by the large thickness of overburden. Because of the small transmissivity and slight hydraulic gradient, water flow is very slow. On the basis of ground-water flow models, Signor and others (in press) estimate that the rate of water flow in southwestern Kansas is on the order of 40 feet per million years. The slow estimated flow rates combined with the continued existence of a geopressured zone in part of the Anadarko Basin is evidence of very small permeability because the geopressure probably developed during Early Pennsylvanian time, about 300 million years ago (Breeze, 1970; Jorgensen, 1993).

The distribution of dissolved-solids concentrations in the lower aquifer units is shown in figure 8. Maximum values exceeding 300,000 mg/L (milligrams per liter) are found in the eastern part of the Anadarko Basin in Oklahoma. With the exception of relatively small areas of outcrop or shallow subcrop adjacent to the Arbuckle, Wichita, and Amarillo Uplifts along the southern boundary of the study area, concentrations of dissolved solids decrease regionally, but not necessarily locally, radially outward from the Anadarko Basin. Dissolved-solids concentrations are less than 10,000 mg/L along the Las Animas Arch in eastern Colorado and along the Nemaha Uplift in northeastern Kansas (fig. 8), where the lower aquifer units receive some recharge. In Kansas, concentrations of dissolved solids in water from the lowermost part of the lower aquifer units, principally the Arbuckle Group, differ noticeably from those in water from the overlying rocks. Along the Nemaha Uplift, dissolved-solids concentrations in water from the Arbuckle Group are larger than in water from the overlying rocks; in the Sedgwick Basin, they generally are smaller. Elsewhere in the lower aguifer units, the dissolved-solids concentrations differ little among samples from the various rock units.

Table 3. Analytical data for water from selected wells completed in the Western Interior Plains and Ozark Plateaus aquifer systems (S.C. Christenson and G.P. Adams, U.S. Geological Survey, written commun., 1988)

[Values of total inorganic carbon (C_T) and values of the log of partial-pressure carbon-dioxide gas in the water (log PCO₂) were calculated by the computer program WATEQF (Plummer and others, 1978); ND, no data; mg/L, milligrams per liter; µg/L, micrograms per liter; <, less than]

well no. (fig.	Site identification (latitude-longitude sequence number)	Distance along flow path (miles)	Well depth (feet below land surface)	Water temperature (degrees Celsius)	pH (standard units)	Dissolved solids, residue on evaporation at 180 degrees Celsius (mg/L)	Calcium, dissolved as Ca (mg/L)	Magnesium, dissolved as Mg (mg/L)	Sodium, dissolved as Na (mg/L)
1	3649000935510 01	0	931.0	B	7.5	232	43	19	2.9
2	3656500940030 01	10.3	1,160.0	N	7.6	175	30	16	1.6
3	3657300940000 01	10.6	1,000.0	ND	8.4	161	32	17	2.3
4	3703450940730 01	20.5	1,100.0	N	7.9	140	25	12	2.0
5	3704000940700 01	20.5	1,258.0	N N	9.7	268	27	13	4.4
9	3714300942500 01	40.1	0.986	ND	71	290	46	18	7.9
7	3714300942618 01	40.8	865.0	N	7.5	218	46	19	8.6
00	3720200941800 01	41.6	601.0	NO NO	7.7	186	33	16	15
6	3725280942555 01	49.7	N	20.5	7.5	267	41	19	43
10	3727560942748 01	52.4	N	20.0	7.9	363	39	17	06
Ξ	3726000943445 01	57.0	1,090.0	23.0	7.8	368	51	23	5
12	3728000943500 01	58.3	910.0	22.0	7.6	381	40	17	98
13	3729180943857 03	62.1	940.0	24.0	7.8	390	37	19	85
14	3727130944106 02		1,140.0	N ON	7.6	470	52	26	93
15	3727130944106 03	62.8	N N	23.5	7.6	505	99	26	16
16	3733080944010 03	66.2	N	24.0	7.5	634	63	27	140
17	3730200945018 01	72.0	473.0	ON	8.0	1,100	84	38	270
18	3734570945938 03		R	24.0	7.2	1,740	80	32	460
19	3733550950234 01	83.9	1,008.0	NO NO	QN	1,770	65	27	530
20	3735310951102 03	91.5	914.0	23.0	7.3	4,750	134	63	1,600
21	3738290952017 03		S	27.5	7.2	6,030	153	99	2,100
22	3746340951747 03	102.1	ND	ND ND	7.0	8,050	195	26	2,800
23	3744270952527 01	107.5	1,000.0	ND ND	Q.	ND	450	370	8,700

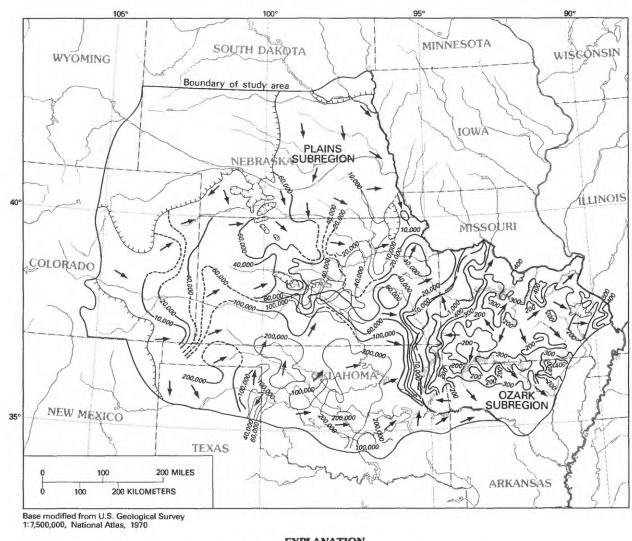
Table 3. Analytical data for water from selected wells completed in the Western Interior Plains and Ozark Plateaus aquifer systems (S.C. Christenson and G.P. Adams, U.S. Geological Survey, written commun., 1988)—Continued

Well no. (fig. 7)	Potassium, dissolved as K (mg/L)	bicar- bonate, dissolved as HCO ₃ (mg/L)	Sulfide, dissolved as S ⁻² (mg/L)	Sulfate, dissolved as SO ₄ (mg/L)	Chloride, dissolved as Cl (mg/L)	Fluoride, dissolved as F (mg/L)	Silica, dissolved as SiO ₂ (mg/L)	Iron, total as Fe (μg/L)	Manga- nese, total as Mn (μg/L)	C _T , calculated (mg/L)	Log PCO ₂ ,
-	9.0	220	N N	13	5.2	ND	00	QN N	QN	3.9	-2.222
2	ND	160	R	7.6	3.9	QN.	00	70	ND	2.8	-2.453
3	7.	180	R	8.0	4.8	0.1	00	100	ND	2.9	-3.220
4	∞.	120	N	12	4.8	.1	7	40	N	2.0	-2.853
2	N Q	130	N N	13	6.3	ND	9	09	N Q	2.3	-2.547
9	N	220	S	12	8.2	.2	7	40	NO	4.0	-2.124
7	-	230	N	13	11	.2	8	40	N	4.1	-2.201
00	Q.	180	R	12	11	€;	00	140	N	3.1	-2.502
6	4	220	R	21	09	3.	10	70	N	3.8	-2.199
10	4	350	ND	24	53	1.1	6	220	N N	5.9	-2.403
11	∞	230	QN N	42	59	κi	2	180	0	3.8	-2.480
12	4	330	N N	22	55	6.	10	10	ND	5.6	-2.119
13	4	280	0.9	19	75	9.	ND	270	2	4.6	-2.388
14	N	310	N	26	110	3.	6	059	R	5.4	-2.190
15	2	290	4.0	39	130	9.	N	<10	3	4.3	-2.186
16	9	320	4.0	47	182.0	∞.	ND	70	4	5.5	-2.035
17	ND	350	R	110	380	1.1	14	089	N	5.8	-2.564
18	17	380	20	09	710	NO ON	ND	N	ND	6.5	-1.740
19	ND	340	ND	4	720	NO NO	ND	N	N N	5.9	-2.058
20	35	340	40	40	2,700	ND	ND	S	S	5.1	-1.944
21	42	420	09	20	3,410	N	R	N N	S	6.3	-1.697
22	37	470	30	10	4,700	ND	N	S S	N	8.6	-1.526
23	R	630	N N	QN.	15,000	N N	10	3,000	QN.	11	-1.941

Table 4. Selected saturation indices for ground water in the Western Interior Plains and Ozark Plateaus aquifer systems (S.C. Christenson and G.P. Adams, U.S. Geological Survey, written commun., 1988)

(Saturation indices calculated from analytical data in table 3 by the computer program WATEQF (Plummer and others, 1978) using saturation index equal to Ion Activity Product divided by equilibrium constant; negative values (-) indicate undersaturation; positive values indicate oversaturation; ND indicates no data]

Well no. (fig. 7)	Site identification (latitude-longitude- sequence number)	Distance along flow path (miles)	Aragonite	Calcite	Chalcedony	Dolomite	Gypsum	Halite	Quartz
1	3649000935510 01	0	-0.253	-0.102	-0.235	-0.349	-2.581	-9.361	0.287
2	3656500940030 01	10.3	420	269	269	602	-2.921	-9.736	.287
3	3657300940000 01	10.6	.426	.578	243	1.094	-2.891	-9.490	.280
4	3703450940730 01	20.5	319	168	295	445	-2.774	-9.543	.228
2	3704000940700 01	20.5	573	403	162	914	-2.718	-9.085	.162
9	3714300942500 01	40.1	327	170	293	550	-2.591	-8.729	.230
7	3714300942618 01	40.8	208	057	235	288	-2.564	-8.510	.287
00	3720200941800 01	41.6	240	880	236	281	-2.705	-8.318	.287
6	3725280942555 01	49.7	218	071	217	182	-2.439	-7.150	.283
10	3727560942748 01	52.4	.325	.473	227	.875	-2.437	-6.890	.275
11	3726000943445 01	57.0	.198	.344	-1.031	.671	-2.089	-7.079	541
12	3728000943500 01	58.3	.046	.192	222	.328	-2.461	-6.898	.272
13	3729180943857 03	62.1	.162	307	N	999.	-2.559	-6.773	N
14	372713094410602	62.8	.010	.161	184	.233	-2.299	-6.553	.339
15	3727130944106 03	62.8	911.	.264	NO ON	.533	-2.126	-6.487	N N
16	3733080944010 03	66.2	.105	.249	N ON	.472	-2.031	-6.197	N N
17	3730200945018 01	72.0	.566	717.	800.	1.310	-1.620	-5.586	.530
18	3734570945938 03	81.7	125	.020	N	013	-1.968	-5.124	ND
19	3733550950234 01	83.9	019	.130	ND	.141	-2.167	-5.038	ON
20	3735310951102 03	91.5	056	060.	ON	.192	-2.188	-4.064	S
21	3738290952017 03	100.7	042	.100	ND	.231	-2.509	-3.869	N N
22	3746340951747 03	102.1	208	057	ND	188	-2.705	-3.601	ON
23	3744270952527 01	107.5	.654	.803	106	1.823	N	-2.674	.405



LINE OF EQUAL DISSOLVED-SOLIDS CONCENTRATION
IN WATER MOSTLY FROM MIDDLE ORDOVICIAN,
UPPER ORDOVICIAN, SILURIAN, AND DEVONIAN
ROCKS—Dashed where appproximately located. Interval,
in milligrams per liter, is variable

LINE OF EQUAL DISSOLVED-SOLIDS CONCENTRATION
IN WATER MOSTLY FROM UPPER CAMBRIAN AND
LOWER ORDOVICIAN ROCKS—Dashed where approximately
located. Interval, in milligrams per liter, is variable

LIMIT OF LOWER UNITS IN THE WESTERN INTERIOR
PLAINS AND OZARK PLATEAUS AQUIFER SYSTEMS

APPROXIMATE BOUNDARY BETWEEN PLAINS AND
OZARK SUBREGIONS

APPARENT DIRECTION OF LATERAL GROUND-WATER FLOW

Figure 8. Dissolved-solids concentrations in water from lower units of the Western Interior Plains and Ozark Plateaus aquifer systems.

Movement of ground water in the lower aquifer units, based on regional-flow simulation (Signor and others, in press), is very complex, and the relation between dissolved-solids concentration and flow direction is variable (fig. 8). The variable direction of flow implies but slight movement in

the weakly defined flow system. Northeasterly flow in the western part of the lower aquifer units is directed to the east-southeast along the Central Kansas Uplift where it meets generally southerly flow from the northernmost extension in Nebraska. Where chemical data are available from these parts of the lower aguifer units, the concentration of dissolved solids generally increases downgradient. In the southern part of the lower aquifer units, ground water apparently moves radially outward from the Anadarko Basin, and the concentration of dissolved solids decreases downgradient. The decrease in dissolved-solids concentrations along flow lines as the transition zone is approached is due to mixing with more dilute water from above (S.C. Christenson and G.P. Adams, U.S. Geological Survey, written commun., 1988). In central Kansas, the differences in dissolved-solids concentrations between water from the Arbuckle Group and that from the overlying rocks are accompanied by differences in fluid levels, indicating potential for vertical movement of brine in these areas (Carr and others, 1986, p. 37-47).

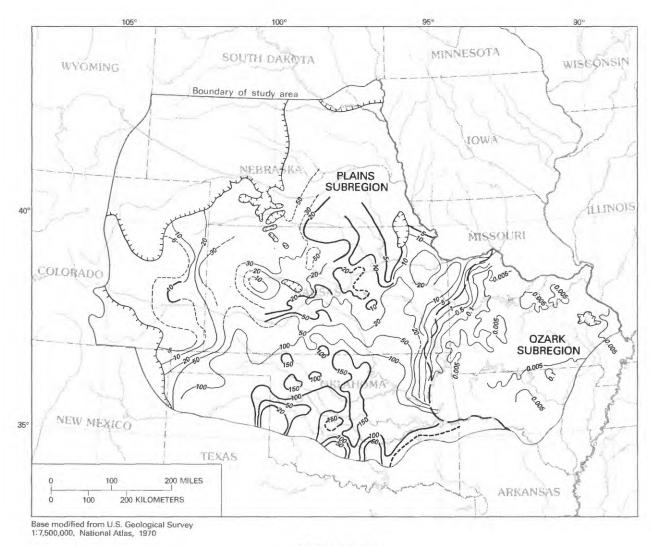
Virtually all water samples from the lower aquifer units are a sodium chloride type. Chloride concentrations in water from the units range from less than 5,000 mg/L along the Las Animas Arch to more than 150,000 mg/L in the Anadarko Basin. The distribution of chloride concentrations, shown in figure 9, generally parallels that of dissolved solids; that is, water with the largest concentrations of dissolved solids generally contains the largest concentrations of chloride. In a large part of the Central Kansas Uplift, sodium-to-chloride ratios in water samples from the lower- most part of the lower aquifer units (Arbuckle Group) are larger than 0.8 (fig. 10), typically near that of seawater (0.85); in water from rocks over-lying the Arbuckle, ratios are somewhat smaller, between 0.7 and 0.8 (all ion ratios given in this report are calculated from values in milliequiva- lents per liter). These slight differences in ion ratios, as well as the differences in dissolved-solids concentrations previously discussed, may be related in part to withdrawal and injection of water in connection with oil production. Carr and others (1986, table 3) estimated that for 1980, 76 percent of the oilfield brine produced in Kansas was disposed of by injection to the Arbuckle Group, but only 13 percent originated from it.

Farther south, the sodium-to-chloride ratios tend to increase with decreasing chloride concentration. Locally larger ratios are found in water along the Las Animas Arch where the lower aquifer units receive some recharge that has a relatively larger sodium-to-chloride ratio. Ratios larger than 0.8 near the Amarillo-Wichita Uplift, together with smaller concentrations of dissolved solids and chloride, may be the result of dilution with meteoric water during Paleozoic time (Dutton and Land, 1985). Sodium-to-chloride ratios greater than 1.0 adjacent to the transition zone may reflect recharge of sodium-rich water through the overlying Western Interior Plains confining system.

In water from most of the lower aguifer units, the ratios of calcium to magnesium are about 2.5 (fig. 11), typical of oilfield brines (White, 1960). In the deep basins near the southern boundary of the study area, increased values of calcium-tomagnesium ratios (locally larger than 5.0) generally correspond with areas of largest chloride concentrations and areas having a sodium-tochloride ratio of about 0.8. This correlation suggests that the brine in this area may be a diagenetically altered paleoevaporative brine. A small area in the southeast corner of Colorado where the ratios are generally less than 1.0 may represent a zone of magnesium enrichment resulting from dedolomitization or other (unknown) causes.

In most of Oklahoma and southern Kansas, the ratios of chloride to sulfate in water from the lower aquifer units exceed 300 (fig. 12), reaching a maximum of more than 5,000 in northeastern Oklahoma. To the south of that area, in the areas of largest chloride concentrations on the eastern flank of the Anadarko Basin and along the Nemaha Uplift, chloride-to-sulfate ratios range from about 300 to 1,000. Over most of the Central Kansas Uplift, chloride-to-sulfate ratios in water from the Arbuckle Group, the lowermost permeable part of the lower aquifer units, are much smaller than those in water from the overlying rocks (fig. 12). Although the chloride-to-sulfate ratios appear to be related primarily to the concentrations of chloride, sulfate concentrations in water from the Arbuckle Group are significantly larger than those in water from the overlying rocks in the areas where sufficient analytical data are available to make comparisons.

The hydrochemical character of water moving southeastward from eastern Nebraska is different from that of water in most of the rest of the lower aquifer units. Dissolved-solids concentrations are generally less than 20,000 mg/L (Jorgensen and others, 1986) and increase southeastward; sodiumto-chloride ratios decrease southeastward. The



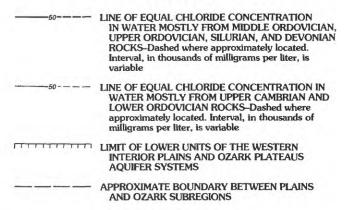
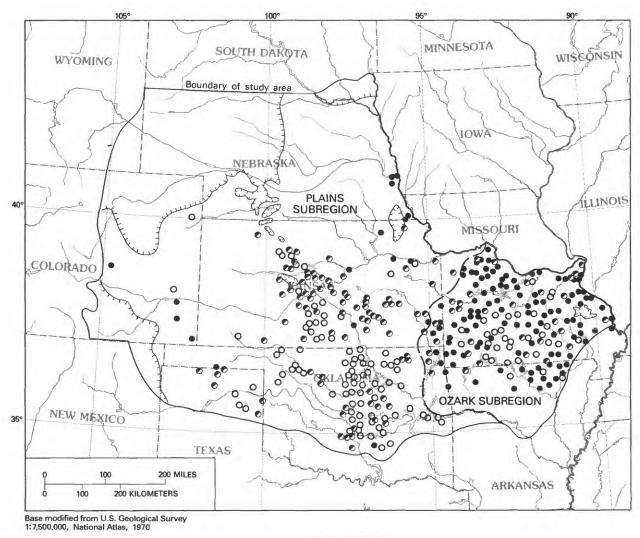


Figure 9. Chloride concentrations in water from lower units of the Western Interior Plains and Ozark Plateaus aquifer systems.

origin of this water is unknown, but Jorgensen and others (1986) suggest it may be at least in part diagenetically altered meteoric water that entered the aquifer in Paleozoic time.

Confining Unit and Upper Aquifer Unit

Because of extensive erosion near the end of Mississippian time, the upper aquifer unit and the confining unit separating the upper and lower aqui-



RATIO OF CONCENTRATIONS OF SODIUM TO CHLORIDE IN WATER FROM LOWER UNITS OF THE WESTERN INTERIOR PLAINS AND OZARK PLATEAUS AQUIFER SYSTEMS-lon ratios were determined from milliequivalent values of sodium and chloride concentrations

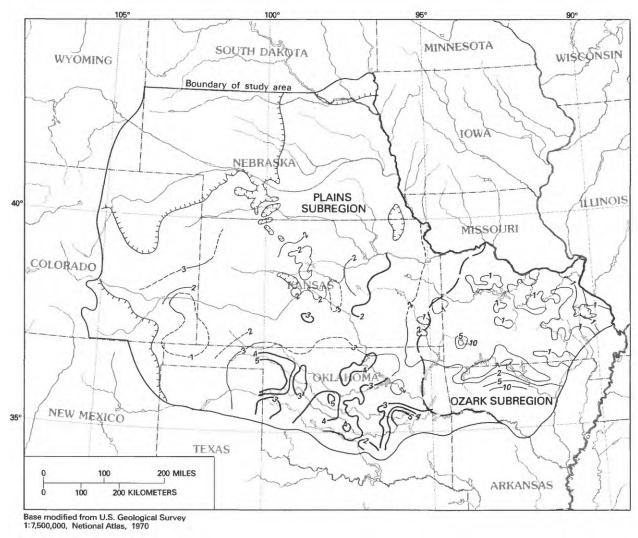
- O Less than 0.8
- 0.8 to 1.0
- Greater than 1.0

LIMIT OF LOWER UNITS OF THE WESTERN
INTERIOR PLAINS AND OZARK PLATEAUS
AQUIFER SYSTEMS

— — APPROXIMATE BOUNDARY BETWEEN PLAINS
AND OZARK SUBREGIONS

Figure 10. Ratios of concentrations of sodium to chloride in water from lower units of the Western Interior Plains and Ozark Plateaus aquifer systems.

fer units of the Western Interior Plains aquifer system have been removed over large parts of the Plains subregion, and rocks of the Western Interior Plains confining unit directly and unconformably overlie the lower aquifer units. The confining unit consists principally of the Chattanooga Shale; the rocks of the upper aquifer unit consist predominately of limestone of Mississippian age. Locally, the confining unit may be missing, and in these areas the upper and lower aquifer units are hydraulically connected. The confining unit is included in this discussion of water chemistry because a sandstone layer in the Chattanooga Shale is permeable and produces oil in Oklahoma and



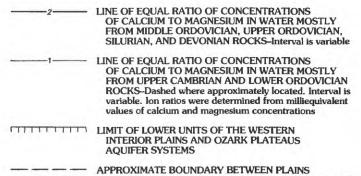
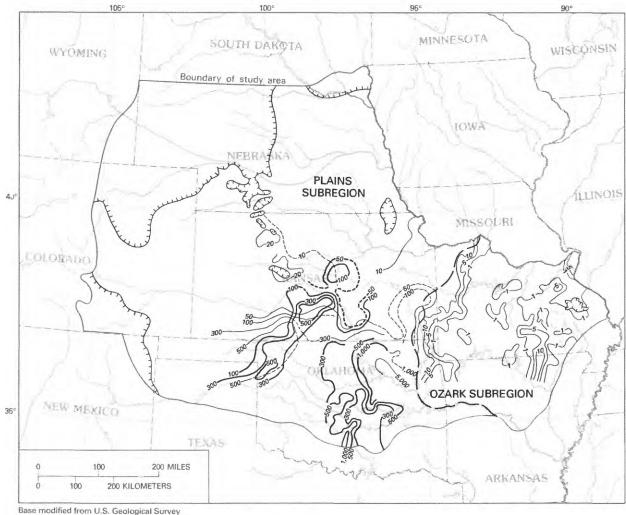


Figure 11. Ratios of concentrations of calcium to Thagnes unit in Water from lower units of the Western Interior Plains and Ozark Plateaus aquifer systems.

Kansas, and chemical analyses of water produced with the oil from this sandstone are available. The chemistry of the water from this sandstone appears to be similar to that of water from the upper aquifer unit; hence, these chemical analyses are an additional source of data that may be, at least in part, indicative of the hydrochemistry of the upper aquifer unit.

The regional distribution of chemical data for the upper aquifer unit of the Western Interior Plains



Base modified from U.S. Geological Survey 1:7,500,000, National Atlas, 1970

EXPLANATION

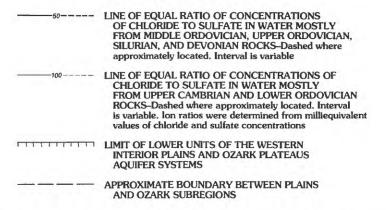


Figure 12. Ratios of concentrations of chloride to sulfate in water from lower units of the Western Interior Plains and Ozark Plateaus aquifer systems.

aquifer system is far more sparse than that for the lower aquifer units; however, the data show generally similar trends. Maximum concentrations of dissolved solids in water from the upper aquifer unit are typically less than 250,000 mg/L, some-

what less than those in water from the underlying units (fig. 13). The general trend of decreasing dissolved-solids concentrations outward from the Anadarko Basin noted in samples from the lower aquifer units generally persists in water of the

upper aquifer unit, but the areas of largest concentrations are displaced northward. In the western and central parts of the Plains subregion, concentrations are generally larger than those in water from the underlying rocks of the lower aquifer units. Median concentrations of less than 10,000 mg/L are found only in the northernmost part of the area. Over the Central Kansas Uplift and the Nemaha Uplift, concentrations in excess of 50,000 mg/L extend into northern Kansas.

The regional directions of ground-water flow in the upper aquifer unit, based on simulation results (Signor and others, in press), are shown in figure 13. As in the underlying lower aquifer units, ground water in the southern part of the Plains subregion appears to move radially outward from the Anadarko Basin. North of the Central Kansas Uplift, the direction of movement is toward the south, changing to eastward on the southern flank of the Central Kansas Uplift where it meets the generally east-northeast flow from the western part

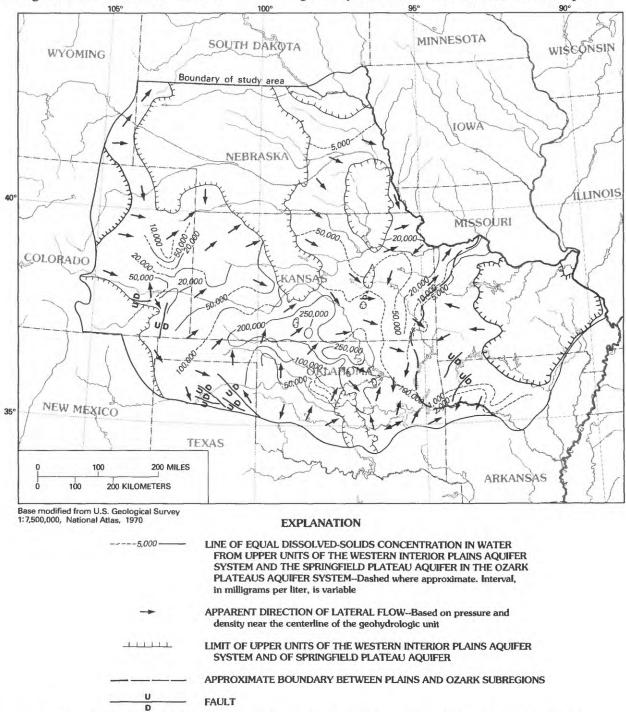


Figure 13. Dissolved-solids concentrations in water from upper units of the Western Interior Plains and Ozark Plateaus aquifer systems.

of the subregion and the northerly flow from the Anadarko Basin.

Water in the upper aquifer unit is almost entirely a sodium chloride type; chloride concentrations locally are larger than 150,000 mg/L (fig. 14). The location of the largest chloride concentrations in this unit is along the Nemaha Uplift in north-central Oklahoma and corresponds closely with that in the lower aquifer units of the aquifer system. However, a broad band of chloride concentrations larger than 100,000 mg/L in central Oklahoma and south-central Kansas lies well to the north of a corresponding band in the lower aquifer units. In general, in Kansas where chloride concentrations exceed 100,000 mg/L, the concentrations are larger than the chloride concentrations representative of the lower aquifer units. However, in Oklahoma this relation is reversed. Throughout this band of large chloride concentrations, ratios of sodium to chloride generally range from about 0.65 to slightly more than 0.8 (fig. 15), possibly indicating an evaporative brine source rather than a dissolved halite source (the sodium-to-chloride ratio of halite is 1.0). Sodium-to-chloride ratios tend to increase with decreasing concentrations of chloride and reach values as large as 5.0 along the Wichita Uplift where the upper aguifer unit is recharged and near the eastern limits of the upper aguifer unit where sodium-rich water leaks downward through rocks of the Western Interior Plains confining system. Along the Nemaha Uplift in northeastern Kansas and the Central Kansas Uplift in central Kansas, chloride concentrations in the upper aquifer unit generally exceed those in the lower aguifer units. Sodium-to-chloride ratios larger than 0.8 in these areas suggest the infiltration of brines derived from dissolution of halite in the overlying Western Interior Plains confining system.

In general, calcium-to-magnesium ratios in water from the upper aquifer unit exceed those in water from the lower aquifer units, probably reflecting the presence of more limestone and less dolomite in the upper aquifer unit. In some small areas, such as near the Las Animas Arch in the west and on the flanks of the Arbuckle Uplift in the south, calcium-to-magnesium ratios are less than 2.0 (fig. 16). Ratios larger than 5.0 generally are associated with the largest chloride concentrations.

Ratios of chloride to sulfate in water from the upper aquifer unit typically range from 100 to 500 (fig. 17). Locally, in the areas of largest chloride concentrations along the Nemaha Uplift in north-central Oklahoma, ratios are as large as 2,000. Chloride-to-sulfate ratios of this magnitude, together with the large chloride concentrations, suggest the addition of brines derived from dissolution of halite in the overlying Western Interior Plains confining system. In the western part of the area, much smaller ratios (as small as 5.0) probably result from downward movement of water containing large concentrations of sulfate from the overlying confining system.

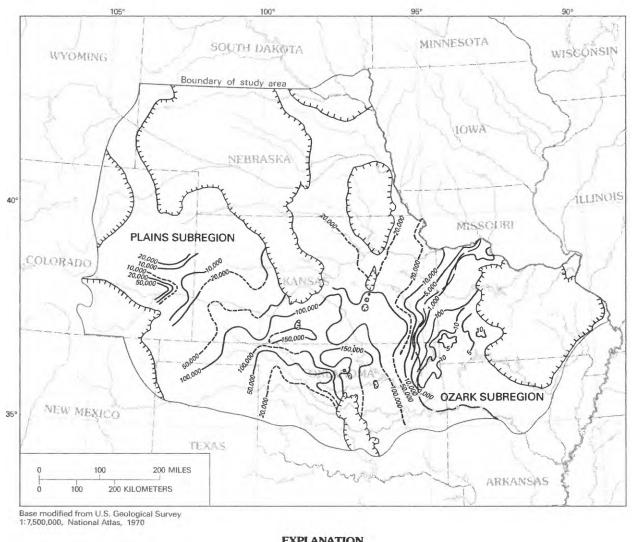
Origin and Evolution of Brines

The chemical composition of all subsurface water is determined by the origin of the water and by its subsequent history; that is, by the chemical, physical, and biological processes that have modified the original composition. These processes generally act together to alter the concentrations of specific solutes.

The importance of organic species in subsurface formation water in sedimentary basins, such as the Anadarko Basin, was reported by Kharaka and others (1986, p. 111):

"Dissolved organic species may play an important role in mineral diagenesis. This role is related to the following chemical properties. (1) They can be the dominant source or sink for hydrogen ion (H+), and thus, directly or indirectly control the pH and buffer capacity of subsurface waters. (2) They behave as reducing agents controlling the oxidation state (Eh) of subsurface waters and the concentrations of multivalent elements (e.g. iron). (3) They can be decarboxylated, thermally or with the aid of bacteria into carbon dioxide and hydrocarbon gases. (4) They form soluble complexes with metals and other inorganic species... "

The brines of the Western Interior Plains aquifer system most likely result from evaporation of a marine brine or dissolution of halite. There are no indications of recent percolation of meteoric water into the aquifer units of the Western Interior Plains aquifer system, except adjacent to the transition zone. The present water chemistry most likely



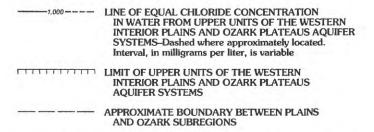
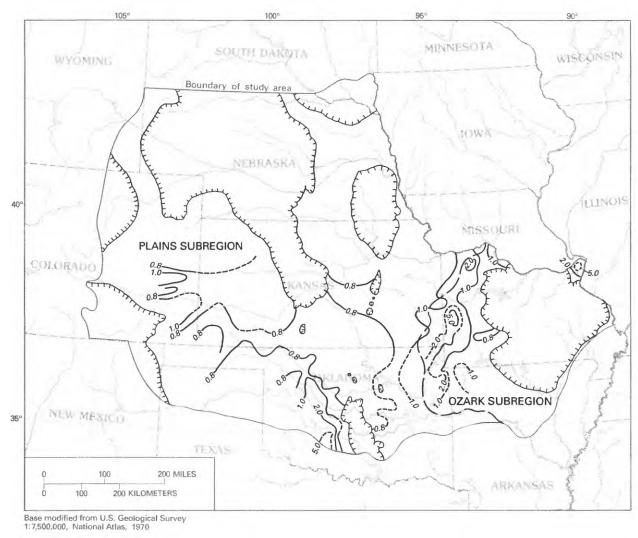


Figure 14. Chloride concentrations in water from upper units of the Western Interior Plains and Ozark Plateaus aquifer systems.

results from modification of the original water of deposition or addition of water to the system early in its history. S.C. Christenson and G.P. Adams (U.S. Geological Survey, written commun., 1988) postulate that the brines in eastern Oklahoma are

evaporative brines on the basis of water chemistry and modeling of water, solute, and temperature.

Extensive evaporite deposits-halite, gypsum, and anhydrite-were formed during Permian time; hence, large parts of the Permian sea must have



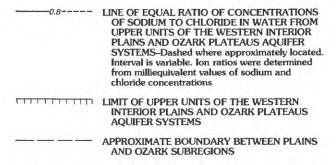
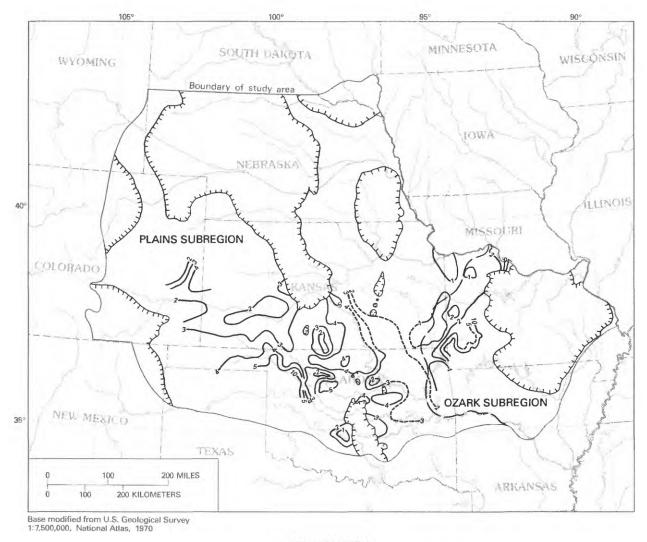


Figure 15. Ratios of concentrations of sodium to chloride in water from upper units of the Western Interior Plains and Ozark Plateaus aquifer systems.

been evaporated to dissolved-solids concentrations of 250,000 to 300,000 mg/L, similar to the concentration of much of the present-day brine. These brines could have moved a limited distance downdip (westward) into the rocks of the Western

Interior Plains aquifer system during the period of regional tilting upward to the east between Late Permian and Late Cretaceous time. It is possible that some evaporative brine, which has a greater density than more dilute water, could have moved



LINE OF EQUAL RATIO OF CONCENTRATIONS
OF CALCIUM TO MAGNESIUM IN WATER FROM
UPPER UNITS OF THE WESTERN INTERIOR
PLAINS AND OZARK PLATEAUS AQUIFER
SYSTEMS—Dashed where approximately located.
Interval is variable. Ion ratios were determined from
milliequivalent values of calcium and magnesium
concentrations

LIMIT OF UPPER UNITS OF THE WESTERN
INTERIOR PLAINS AND OZARK PLATEAUS
AQUIFER SYSTEMS

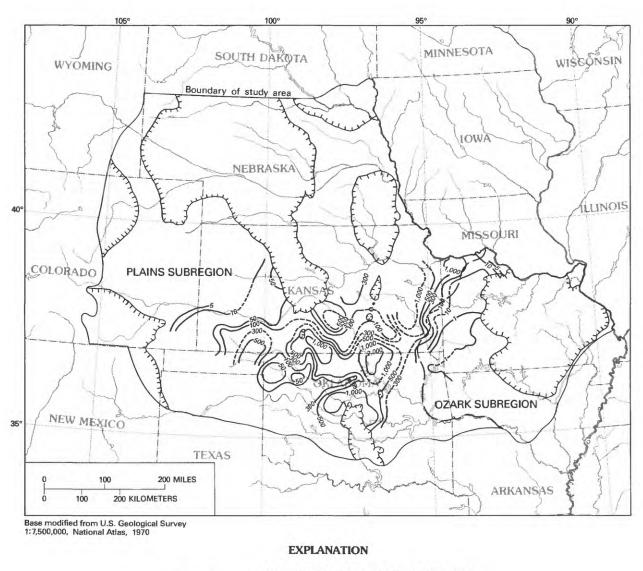
APPROXIMATE BOUNDARY BETWEEN PLAINS
AND OZARK SUBREGIONS

Figure 16. Ratios of concentrations of calcium to magnesium in water from upper units of the Western Interior Plains and Ozark Plateaus aquifer systems.

downward into the Western Interior Plains aquifer system since the Permian. However, little of the water in the aquifer system in north-central and northeastern Oklahoma owes its origin to that source, according to S.C. Christenson and G.P.

Adams (U.S. Geological Survey, written commun., 1988).

If the ground water in the Western Interior Plains aquifer system originated as marine water trapped in the sediments at the time of deposition



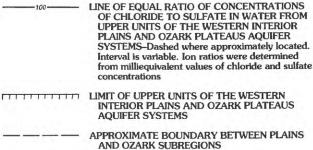


Figure 17. Ratios of concentrations of chloride to sulfate in water from upper units of the Western Interior Plains and Ozark Plateaus aquifer systems.

or marine evaporative brines added to them in Paleozoic time, a variety of mechanisms must have been involved in deriving the present chemical composition. It is generally believed that the proportions of the principal constituents of seawater have not changed significantly since Precambrian time. The present seawater concentrations are as follows (modified from Hem, 1985, table 2):

Constituent	Concentration (milligrams per liter)	Concentration (milliequivalents per liter)
Calcium	410	20
Magnesium	1,350	111
Sodium	10,500	457
Sulfate	2,700	56
Chloride	19,000	540

The present-day ratios are: sodium to chloride, 0.85; calcium to magnesium, 0.2; and chloride to sulfate, 9.6.

Chloride is the most abundant ion in most water samples from the Western Interior Plains aquifer system. Hem (1985, p. 118) notes that, "The chemical behavior of chloride in natural water is tame and subdued compared with the other major ions. Chloride ions do not significantly enter into oxidation or reduction reactions, form no important solute complexes with other ions unless the chloride concentration is extremely high, do not form salts of low solubility, are not significantly adsorbed on mineral surfaces, and play few biochemical roles." Simple concentration or dilution of seawater, therefore, easily could account for the observed concentrations of chloride in the present-day brines (5,000 to 190,000 mg/L).

Bromide is another conservative ion that, like chloride, will remain in solution in very concentrated brines. S.C. Christenson and G.P. Adams (U.S. Geological Survey, written commun., 1988) compared the ratio of bromide to chloride in samples from northeastern Oklahoma near the "transition zone." As shown in figure 18, a plot of bromide and chloride concentrations falls very near the theoretical seawater-evaporation line.

The sodium-to-chloride ratio in most samples from the Western Interior Plains aquifer system is somewhat smaller than that in seawater; the difference is greatest in samples with the largest chloride concentrations. Salts of sodium, like those of chloride, are very soluble, and it is unlikely that sodium has been lost by precipitation. However, sodium ions do enter into ion-exchange processes, and if sodium concentrations are large, sodium ions are adsorbed readily on some clay minerals. Depletion of sodium by ion exchange or adsorption can readily account for the observed sodium-to-chloride ratios if the present chloride

concentrations are the result of the concentration of seawater.

Calcium-to-magnesium ratios in water from the Western Interior Plains aquifer system are typically one order of magnitude or more greater than that of present-day seawater and cannot be explained by simple evaporative concentration. Dolomite is a prominent constituent of the rock: however, dolomite is rarely a primary mineral. Depletion of magnesium and enrichment of calcium in the brines (relative to seawater) is most likely the result of the diagenetic conversion of calcium carbonate to dolomite. Hanshaw and Back (1979, p. 308) show that for calcium-tomagnesium ratios of less than 1.0, dolomitization should proceed spontaneously over time if enough magnesium is available. Simple concentration of seawater would provide sufficiently large concentrations of magnesium ions. Kramer (1969) found that calcium-to-magnesium ratios for brines from dolomitic rocks ranged from about 1.5 to 3.5, and the mean value was very close to equilibrium values for calcite-dolomite.

The large chloride-to-sulfate ratios in most water from the aquifer system—10 to 100 times that of seawater—indicate a large loss of sulfate. Some sulfate may have been removed from the brine by precipitation of gypsum (calcium sulfate). Moreover, sulfate is not a thermodynamically stable species in a reducing environment, such as that involved in the formation of petroleum and natural gas. It is likely that most of the sulfate in the original interstitial water was reduced to sulfide or elemental sulfur, primarily by bacterial action.

Western Interior Plains Confining System

Rocks ranging in age from Late Mississippian through Jurassic cover nearly all of the Plains subregion and comprise the Western Interior Plains confining system. The system is less than 500 feet thick in the northeastern part of the Plains subregion but thickens rapidly to the south and southwest, reaching a maximum thickness of more than 20,000 feet in the deeper parts of the Anadarko Basin. Shale, limestone, and sandstone of Pennsylvanian age predominate in the lower part of the confining system; Permian rocks consist mainly of thick shale, with extensive beds and lenses of halite and gypsum and some minor limestone and sand-

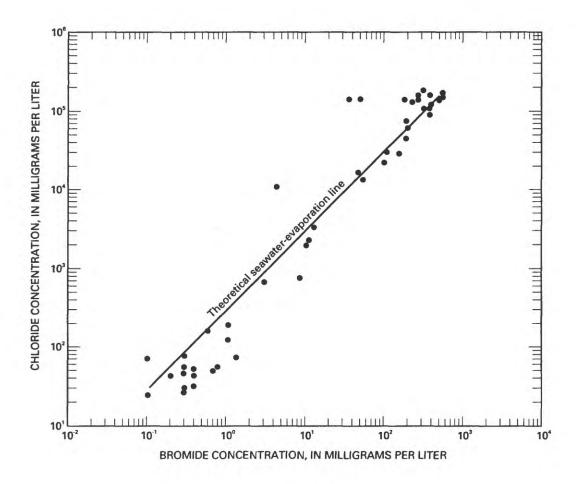


Figure 18. Concentrations of bromide and chloride in water samples from wells completed in the Western Interior Plains and Ozark Plateaus aquifer systems compared to theoretical seawater-evaporation line.

stone. Red beds of Jurassic and Triassic age are present in the northwestern one-third of the Plains subregion. Although the rocks as a whole are classed as a regional confining system, the extensive sandstone and limestone are permeable in the basin shelf areas and locally are usable aquifers or contain prolific oil reservoirs.

Because units of the Western Interior Plains confining system are at or near land surface over much of the Plains subregion, water from shallow wells within the zone of circulation of meteoric water bears little resemblance chemically to water contained in the rocks at depth. Accordingly, this discussion of the hydrochemistry of the confining

system is restricted to conditions found at depths of more than 500 feet. The hydrochemistry of the shallow water-bearing zone (less than 500 feet deep) is described in the section entitled "Shallow Water-Bearing Zone in Pre-Cretaceous Rocks."

The distribution of dissolved-solids concentrations in water from the confining system at depths greater than 500 feet is shown in figure 19. Because both the horizontal and vertical permeability of the sampled units vary greatly, concentrations also vary greatly over relatively short distances. In general, dissolved-solids concentrations in water from the confining system tend to vary inversely with depth. The largest concentra-

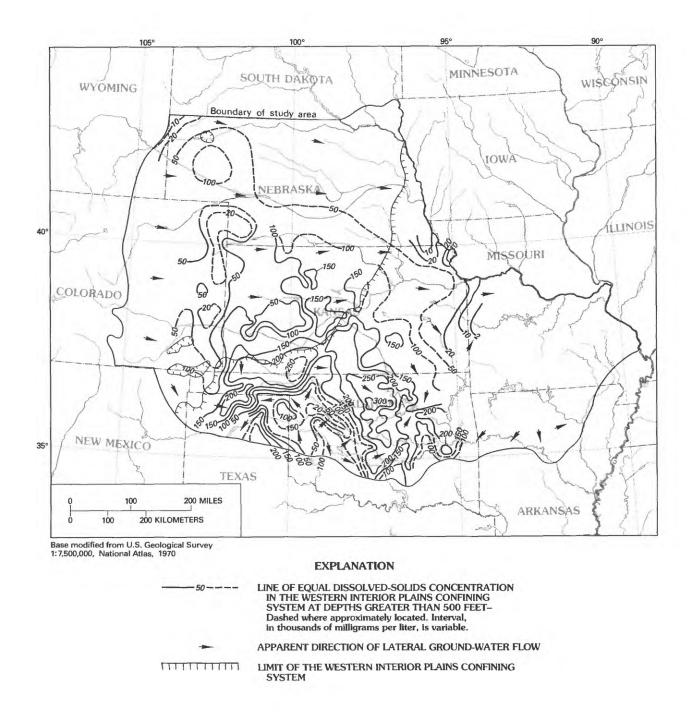


Figure 19. Dissolved-solids concentrations in water from the Western Interior Plains confining system.

tions, in excess of 300,000 mg/L, are in samples from depths of less than 4,000 feet; most samples with concentrations of more than 200,000 mg/L are from depths of less than 6,000 feet. In the Anadarko Basin, where regional concentrations are generally larger than 200,000 mg/L, scattered

samples from Morrowan rocks at depths of as much as 10,000 feet have concentrations of less than 30,000 mg/L. Large differences in dissolved-solids concentrations typically are apparent from differences in sampling depth. This variation in the concentrations of dissolved solids probably is a

function of the depth of the sampled interval below evaporite layers, which are common in the upper part of the confining system. However, in the lower part of the confining system, the source of the brine may not be affected by the overlying halite. For example, Stell (1988) reports that the deuterium and oxygen-18 isotope data of oilfield water from rocks of the Lansing and Kansas City Groups of Pennsylvanian age in the Hugoton Embayment in Kansas can be interpreted as a mixture of evaporative brine water and meteoric water.

The arrows in figure 19 show the apparent direction of regional ground-water flow in the permeable units of the confining system, based on flow simulations by Signor and others (in press). Although there appears to be some radial flow of water around the margins of the Anadarko Basin and some areas of predominantly southerly flow on the southern flanks of the Ozark Uplift, regional movement is primarily eastward across the Plains subregion. No relation between dissolved-solids concentrations and flow patterns is indicated.

Virtually all water from depths of more than 500 feet in the Western Interior Plains confining system is a sodium chloride type. The distribution of chloride concentrations (fig. 20) closely parallels that of dissolved-solids concentrations. Chloride concentrations of more than 180,000 mg/L are reported from wells near the western flank of the Nemaha Uplift in Oklahoma, and concentrations of 50,000 mg/L or greater are common over most of the study area. Only in a few narrow zones near the margins of the confining system are concentrations less than 10,000 mg/L common. Over the Central Kansas Uplift, where the upper aquifer unit of the Western Interior Plains aquifer system is missing, concentrations of chloride near the base of the confining system exceed 100,000 mg/L and are much larger than concentrations in the underlying truncated lower aguifer units.

Ratios of sodium to chloride are greater than 0.8 in most water samples from the confining system (fig. 21). The tendency for sodium-to-chloride ratios to increase with decreasing chloride concentrations, as evidenced along the eastern margin of the area near the transition zone, suggests an additional source of sodium, possibly from ion exchange. Relatively large sodium-to-chloride ratios (near 1.0) in large areas where chloride concentrations exceed 100,000 mg/L, however,

probably reflect the effects of the dissolution of evaporite deposits. A solution of halite and water, which is common in the upper units of the confining system, has a sodium-to-chloride ratio of 1.0.

Calcium-to-magnesium ratios in nearly all samples from the confining system are greater than 1.0; typically in the range of 1.0 to 4.0 (fig. 22). Larger values of calcium-to-magnesium ratios, locally greater than 10, probably are caused by addition of calcium as a result of the dissolution of gypsum deposits.

Concentrations of sulfate are generally smaller in water from the confining system than in the underlying aquifer system; consequently, ratios of chloride to sulfate (fig. 23) are generally larger. The smaller concentrations of sulfate may be due in part to sulfate reduction during the formation of petroleum. On the Central Kansas Uplift, chlorideto-sulfate ratios in water from the lower part of the confining system exceed 1,000 where these rocks overlie the truncated rocks of the lower aquifer units in the Western Interior Plains aquifer system, in which the chloride-to-sulfate ratio is less than 100. Relatively small chloride-to-sulfate ratios (less than 100), often associated with sodium-tochloride ratios greater than 0.9, may be the result of dissolution of gypsum and halite from the extensive evaporite deposits.

Overall, the composition of deep water from the Western Interior Plains confining system probably results from processes similar to those discussed for the underlying aquifer system acting on connate brines and complicated by the precipitation and re-solution of the extensive beds and lenses of halite, gypsum, and anhydrite.

Great Plains Aquifer System

Hydrochemistry of the Great Plains aquifer system has been investigated by many workers. The Great Plains aquifer system is one of the most extensive systems in North America. No regional data synthesis and evaluation of the aquifer characteristics had been undertaken since the classic work of Darton (1905). During the RASA study, Helgesen and others (1982) summarized the important work and the changes in concepts that have occurred since Darton's 1905 study and concluded that conceptualization of the geohydrology was handicapped by confusing nomen-

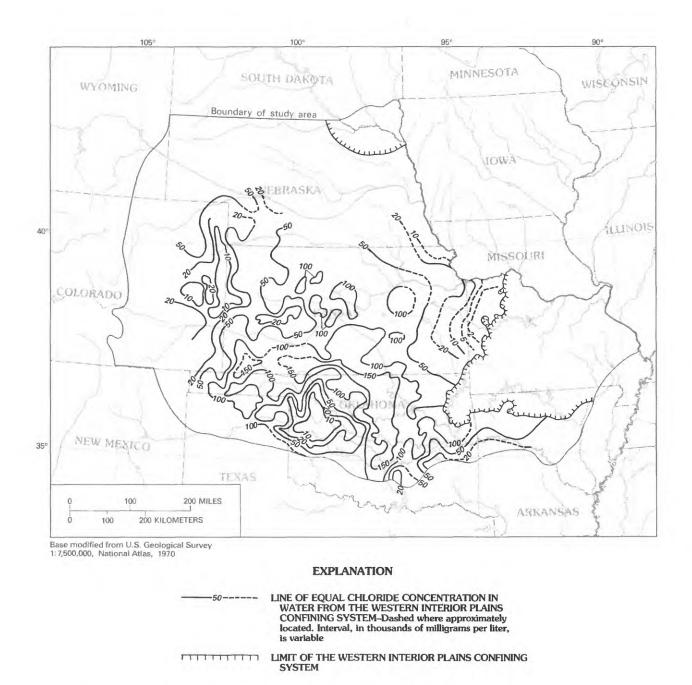


Figure 20. Chloride concentrations in water from the Western Interior Plains confining system.

clature used in describing the various sandstone units of Early Cretaceous age, which had been collectively called the "Dakota aquifer."

Recent reports also include Leonard and others (1983), Jorgensen and others (1986), and papers included in Jorgensen and Signor (1984).

Jorgensen and others (1993) and Helgesen and others (1993) divide the Great Plains aquifer system into three units—a lower aquifer unit consisting primarily of the Cheyenne Sandstone (Apishapa aquifer), a thin confining unit consisting primarily of the Skull Creek Shale (Apishapa

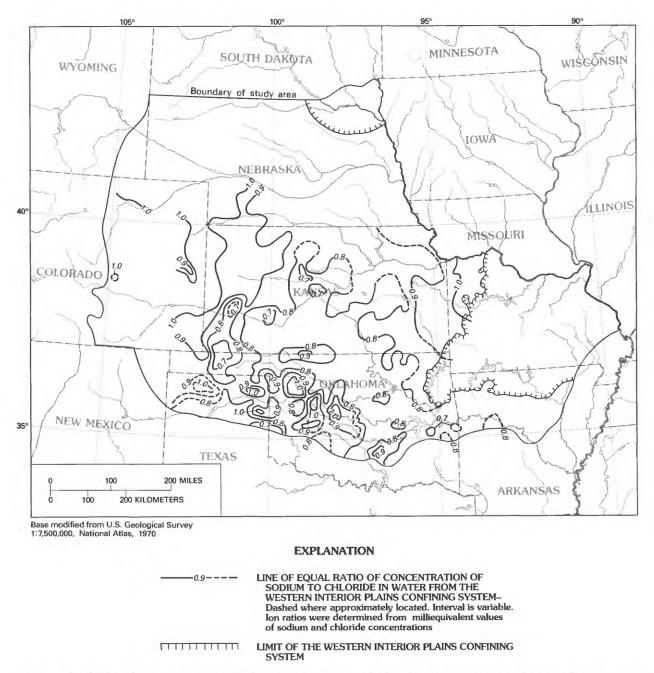


Figure 21. Ratios of concentrations of sodium to chloride in water from the Western Interior Plains confining system.

confining unit), and an upper aquifer unit consisting primarily of the Dakota Sandstone (Maha aquifer). Both aquifer units are composed principally of poorly cemented water-bearing sandstone; the shale confining unit is thin and locally absent. Where water samples from nearby wells can be identified as coming from one or the other of the aquifer units, the water chemistry in the two aquifers is generally similar. Most of the available water samples are from the Maha aquifer, but historically, the two aquifer units often have not been distinguished and the source of many

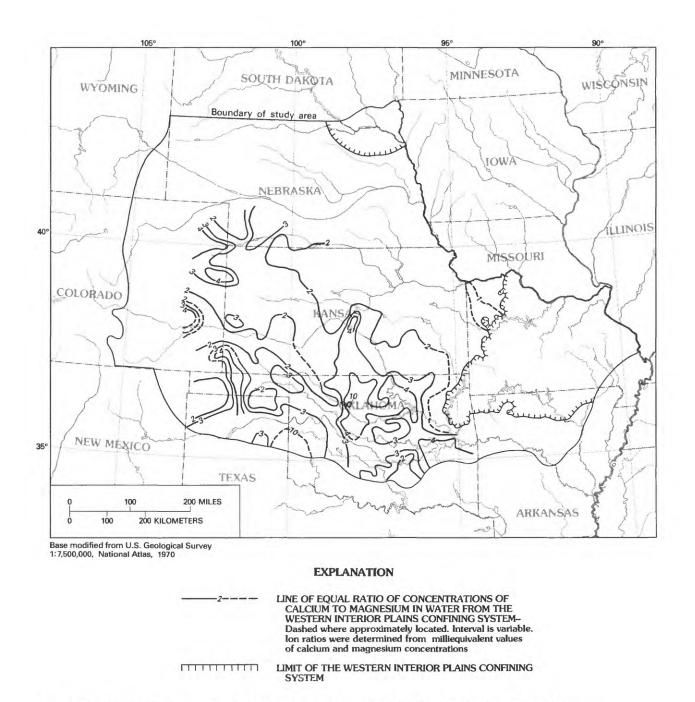


Figure 22. Ratios of concentrations of calcium to magnesium in water from the Western Interior Plains confining system.

samples is uncertain. For these reasons, the discussion of the hydrochemistry in this report will be in reference to the Great Plains aquifer system as a whole.

The generalized distribution of dissolvedsolids concentrations in water from the Great Plains aquifer system is shown in figure 24. In most of the interior part of the aquifer system, concentrations of dissolved solids exceed 5,000 mg/L.

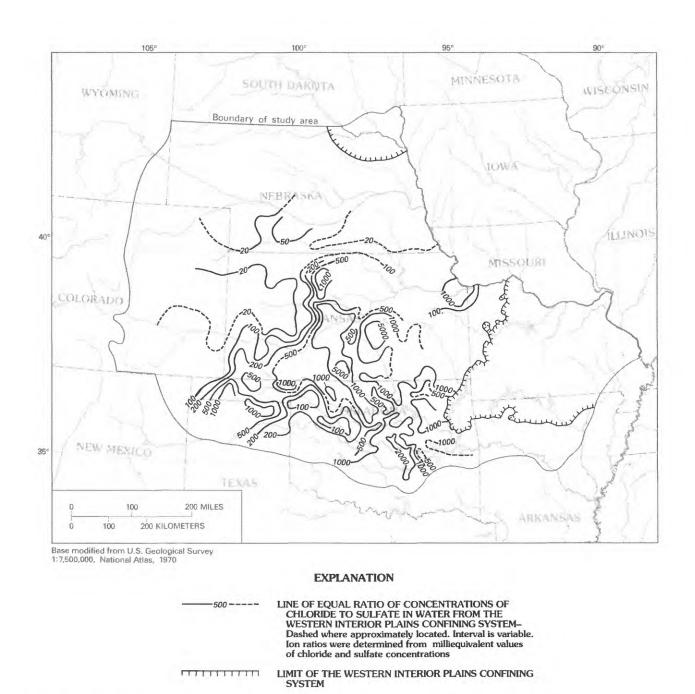


Figure 23. Ratios of concentrations of chloride to sulfate in water from the Western Interior Plains confining system.

Locally, large variations and apparent steep concentration gradients in this part of the system may be the result of differences in sampling depth or of marked lateral differences in permeability. The largest dissolved-solids concentrations, more than 125,000 mg/L, are found in western Nebraska.

Many relatively small areas in Nebraska, Kansas, and Colorado where concentrations are greater than 10,000 mg/L are associated with petroleum production. Lines of equal concentrations describing these areas surround zones generally oriented nearly parallel to flow (fig. 24), suggesting

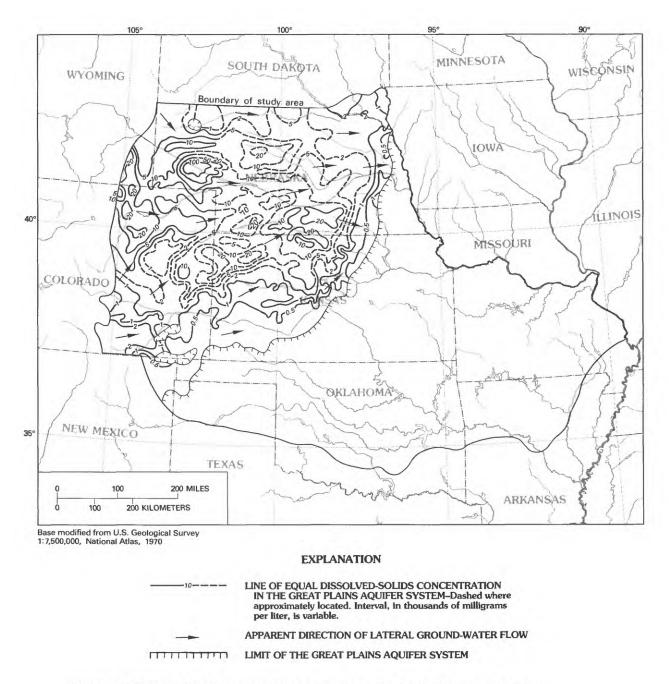


Figure 24. Dissolved-solids concentrations in water from the Great Plains aquifer system.

movement of water along discrete plumes affected by variable permeability in channel sandstone. Concentrations of dissolved solids in the outcrop areas at the northwestern corner of the study area and around the southern and eastern margins of the aquifer system (all areas of recharge) are generally less than 1,000 mg/L.

Water type in the Great Plains aquifer system is much more variable than in the underlying older rocks. In the part of the aquifer system where dissolved-solids concentrations exceed

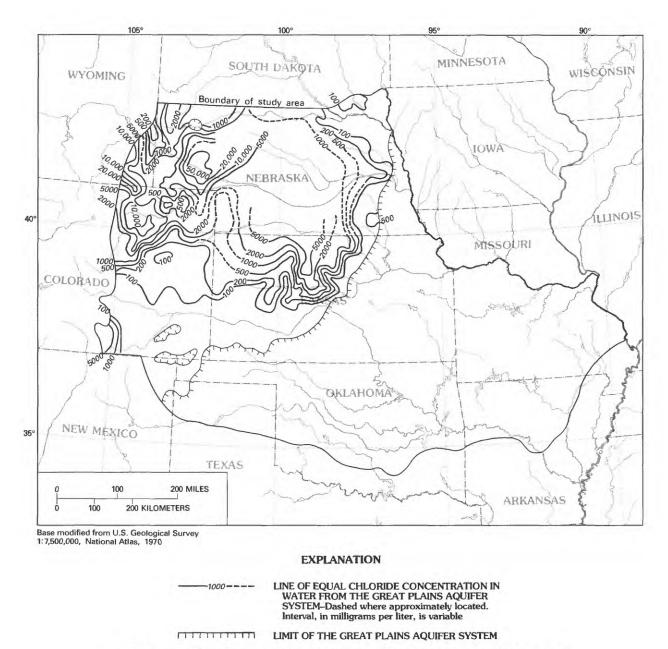


Figure 25. Chloride concentrations in water from the Great Plains aquifer system.

5,000 mg/L, the water is generally a sodium chloride type. Sodium continues as the predominant cation in the more dilute water in the southern part of the system, but the principal anions are bicarbonate and sulfate or a mixture of the two. Primarily calcium bicarbonate type water is found in most of the outcrop areas. Small areas of calcium sulfate and sodium chloride type water exist near the eastern boundary of the system in Kansas.

Calcium sulfate water predominates in northeastern Nebraska and southeastern South Dakota.

Concentrations of chloride in water from the Great Plains aquifer system range from less than 100 mg/L near the outcrop area to more than 50,000 mg/L in samples from the Nebraska Panhandle on the northeastern flank of the Denver Basin (fig. 25). Although chloride concentrations in samples from a given location generally increase

with depth, the largest concentrations are not found at the greatest depths. The maximum observed concentrations were from depths of about 4,000 feet; samples from depths as great as 9,700 feet in the deepest parts of the Denver Basin have chloride concentrations of less than 20,000 mg/L. Steep concentration gradients in the areas of largest concentrations suggest vertical movement of water in the system. In only three relatively small areas, all of which may be affected by the intrusion of saline water from below, is the concentration of chloride greater than that of present-day seawater (about 19,000 mg/L).

Even in the oilfield areas, where the water is a sodium chloride type and concentrations of chloride exceed 5,000 mg/L, the ratio of sodium to chloride is less than 0.85 (the ratio in present-day seawater) in only a few samples. Throughout most of the aquifer system, the ratio is greater than 1.0 (fig. 26). Near outcrop areas, where concentrations of chloride are small, the sodium-to-chloride ratios are much larger, in many samples greater than 10.

Ratios of calcium to magnesium in the Great Plains aquifer system are shown in figure 27. The ratio of calcium to magnesium exceeds 0.2, the value for present-day seawater, in virtually all samples of water from the Great Plains aquifer system. Although a few samples have calcium-tomagnesium ratios greater than 5.0, the ratio over most of the system ranges from about 0.5 to 3.5 and bears little apparent relation to dissolved-solids concentrations, chloride concentrations, sampling depths, or water types. Ratios of calcium to magnesium larger than 5.0 are associated with sodium chloride water containing about 10,000 mg/L of dissolved solids in the deeper parts of the Denver Basin and with calcium bicarbonate water containing about 500 mg/L of dissolved solids near the eastern boundary of the aquifer in Kansas. Through much of the aquifer system, calcium-tomagnesium ratios between 0.8 and 3.0 are associated with a variety of water types and concentrations.

Ratios of chloride to sulfate range from less than 0.1 to more than 1,000 (fig. 28). Ratios of less than 1.0 typically are associated with chloride concentrations of less than about 100 mg/L. In most of the oil-producing areas, where chloride concentrations are largest, chloride-to-sulfate ratios are generally greater than 100.

The great diversity in chemical composition of water samples from different parts of the Great Plains aguifer system indicates the effects of various processes. Water associated with the occurrence of petroleum and natural gas in the Denver Basin is similar to many oilfield brines. The rocks of the Great Plains aquifer system, however, are primarily deltaic and strandline deposits, and the water in which they were deposited was probably fresher than seawater. Moreover, there was probably opportunity for the addition of meteoric water before deep burial and compaction of the rocks. Circulation of water in the Denver Basin is slow, and the solute concentrations indicate long residence times for the water. Removal of sulfate ions is reflected in the large chloride-to-sulfate ratios. Sodium-to-chloride ratios greater than 0.9 in areas of largest chloride concentrations suggest the addition of sodium chloride, either by the movement of very saline water from below or by dissolution of halite from the underlying rocks.

Where the rocks crop out in the southwestern corner of the aquifer system extent, meteoric water enters the system as recharge. Samples 1 to 3 in figure 29 illustrate the change in concentration and composition as this water moves downgradient. The predominant anion in all three samples is bicarbonate. Very dilute calcium bicarbonate type water (sample 1) increases in concentration as it mixes with more saline water and dissolves the sparse calcite cement in the rocks (sample 2). These processes continue downgradient, but at greater distances from the outcrop (sample 3), the almost total replacement of calcium and magnesium by sodium is consistent with natural softening of the water by ion-exchange processes.

Samples 4 to 7 illustrate the change in water type and solute concentration as water moves away from the recharge area at the outcrops in the north-western corner of the study area. Water from shallow depth (145 feet) near the outcrop is a calcium sodium bicarbonate type and is very dilute (sample 4). Southeast of the outcrop, water is found at increasingly greater depths with increasing concentrations of dissolved solids. The steady increase in bicarbonate concentration suggests continued solution of the calcite cement, and the large increase of sulfate ion in sample 5 (about 2,600 feet) would suggest mixing with water from the underlying gypsiferous shale. The expected



Figure 26. Ratios of concentrations of sodium to chloride in water from the Great Plains aguifer system.

addition of calcium ion, however, does not appear; the observed large increase in sodium concentration leads to the supposition that calcium and magnesium from solution are being replaced by sodium from clay through ion exchange. Sample 6 (about 5,400 feet) shows the effects of mixing of shallower water with the sulfate-poor, chloride-rich

brine that predominates at depths of greater than 6,000 feet (sample 7).

Calcium sulfate type water is predominant at moderate depths in northeastern Nebraska and southeastern South Dakota. The source for this water is probably upward leakage through the underlying Pennsylvanian shale, which includes lenses and beds of gypsum and anhydrite. Infiltra-

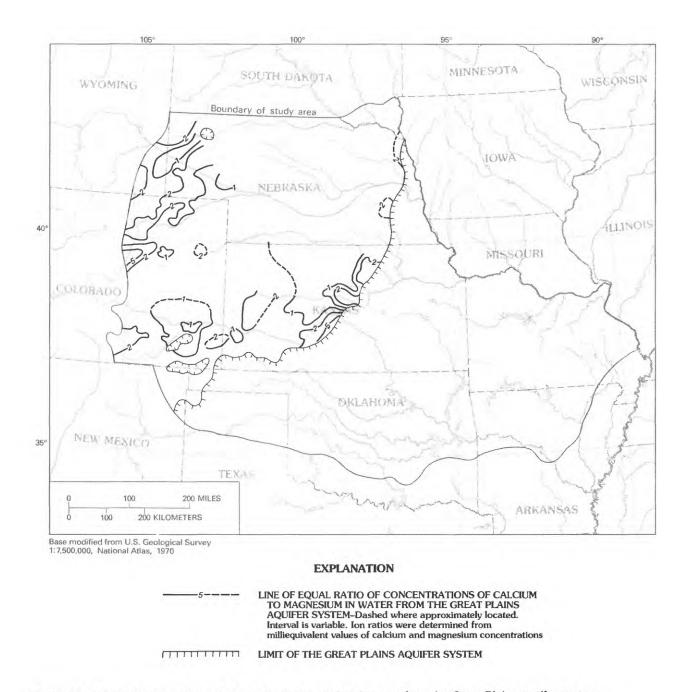
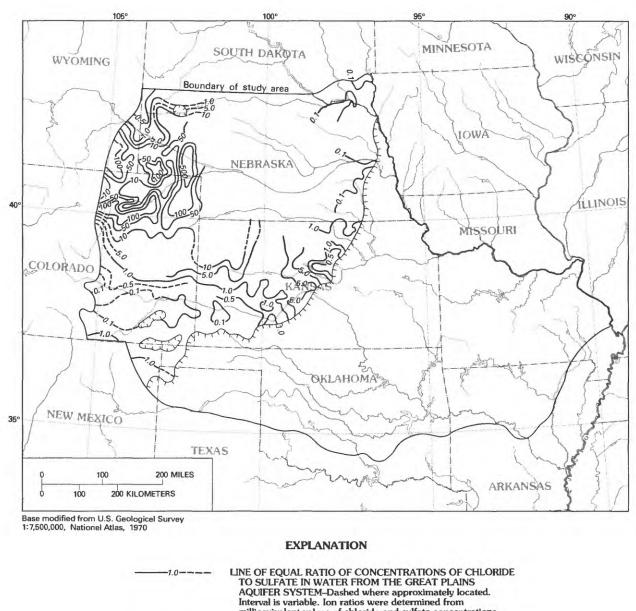


Figure 27. Ratios of concentrations of calcium to magnesium in water from the Great Plains aquifer system.

tion of meteoric water through the overlying Cretaceous shale also could be a source of calcium and sulfate; this shale commonly contains abundant gypsum (Tourtelot, 1962).

In the area of outcrop and shallow subcrop of the Great Plains aquifer system in eastern Kansas and Nebraska, the variety of water types and dissolved-solids concentrations reflects addition of water from both above and below. Meteoric water infiltrates directly in the outcrop areas, and freshwater of calcium bicarbonate type moves downward locally from the overlying High Plains aquifer. The underlying rocks contain saline water, as well as beds and lenses of evaporite. Hence,



milliequivalent values of chloride and sulfate concentrations

LIMIT OF THE GREAT PLAINS AQUIFER SYSTEM

Figure 28. Ratios of concentrations of chloride to sulfate in water from the Great Plains aquifer system.

calcium sulfate water is derived from solution of gypsum, and sodium chloride is added from upward movement of brine or from solution of halite. Mixing of water from these diverse sources gives rise to complex and often unpredictable water chemistry.

Water from the Great Plains aquifer system in the study area is an important source of supply for human use only in the eastern outcrop area in Kansas and Nebraska. Near the southern boundary of the aquifer in Kansas, water in parts of the system is suitable for irrigation and for domestic use. However, more dilute water generally can be had from shallower depths in the High Plains aquifer, and the water from the Great Plains aquifer system commonly is not used. Over most of the

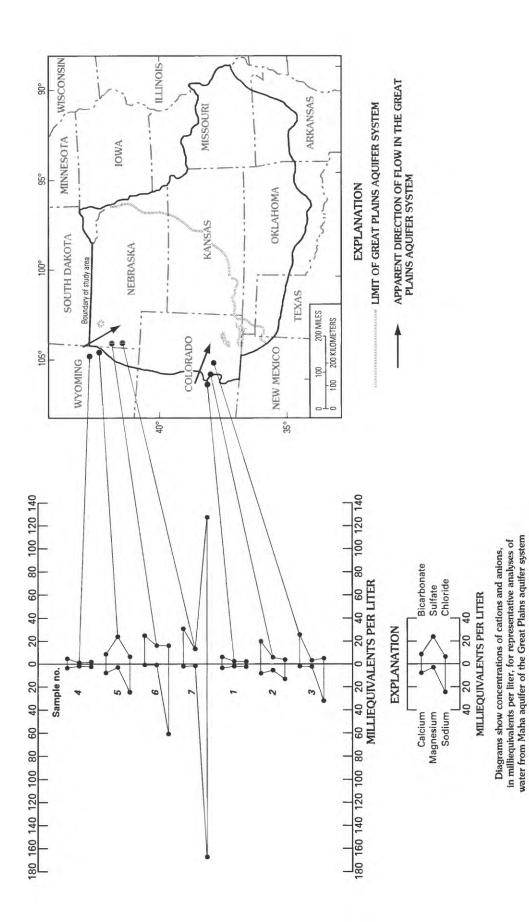


Figure 29. Changes in quality of water along selected flow paths in Great Plains aquifer system.

interior part of the aquifer system in the study area, the aquifer system is too deeply buried to be considered a viable source for water supplies.

Ozark Subregion

The Ozark subregion was subject to repeated periods of uplift and emergence during Paleozoic time, as evidenced by widespread unconformities. Fracturing followed by subaerial erosion and weathering of the massive carbonate rock beds, including the development of karst features, resulted in very large transmissivities. In the Ozark subregion, where the rocks are exposed, the presence of sinkholes and other collapse structures indicates that karstification is still continuing. Geohydrologic units in the Ozark subregion occur at shallower depths compared to units in the Plains subregion previously discussed.

Ozark Plateaus Aquifer System

The Ozark Plateaus aquifer system is divided by Jorgensen and others (1993) into three aquifers separated by two confining units; however, the confining units are thin, leaky, and locally absent. Although flow patterns are generally similar throughout the aquifer system, differences in aquifer materials between the Springfield Plateau aquifer and the underlying Ozark and St. Francois aquifers have resulted in observable differences in water chemistry.

Ozark and St. Francois Aquifers

The general direction of ground-water flow and the distribution of dissolved-solids concentrations in water from the Ozark and St. Francois aquifers are shown in figure 8. Ground water in the Ozark and St. Francois aquifers moves radially out from a southwest-northeast trending topographic high near the center of the Ozark subregion toward discharge areas on the flanks of the Ozark Uplift and toward the transition zone on the western and southern margins of the subregion. The water occurs under conditions ranging from unconfined to confined. Concentrations of dissolved solids in water from the Ozark and St. Francois aquifers are small, typically less than 500 mg/L and rarely exceeding 1,000 mg/L. Although the predominate

cations differ from place to place and mixed-cation types (calcium and magnesium) are most common, the predominate anion in the water from these aquifers is bicarbonate.

Because water moves rapidly through the rocks of these aquifers, most depositional water was flushed away long ago. The present water chemistry is primarily the result of dissolution of the aquifer materials. Water in the system is generally undersaturated with respect to calcite and dolomite, but the degree of undersaturation decreases with increasing distance from the recharge areas (table 4, samples 1-9). Chloride concentrations are generally small (fig. 9), typically less than 5 mg/L. Ratios of sodium to chloride show little apparent pattern (fig. 10) and range from less than 0.4 to more than 10.

In most water samples from the Ozark and St. Francois aquifers, the ratio of calcium to magnesium is slightly larger than 1.0 (fig. 11), appropriate for dilute water near equilibrium with the predominately dolomitic rocks comprising the aquifers. Locally smaller values may represent loss of calcium either through dedolomitization or through precipitation of calcite from loss of carbon dioxide during circulation.

Sulfate, like chloride, is a minor constituent in the water from these aquifers; the ratio of chloride to sulfate is typically about 1.0 in the Ozark subregion (fig. 12). In a small area in the southeastern part of the subregion in northern Arkansas and southern Missouri, water from the St. Francois aquifer contains more than 100 mg/L of chloride, and the chloride-to-sulfate ratios are greater than 10, possibly reflecting the presence of lingering traces of connate marine water.

The Ozark aquifer is the most extensively used source of ground water in the Ozark subregion. The dilute bicarbonate water is suitable for nearly all human uses—public supply, irrigation, domestic use, and most industrial applications. Water from the St. Francois aquifer is equally satisfactory, and the St. Francois is the common source of water supply in areas where the Ozark aquifer is thin or absent near the St. Francois Mountains.

Springfield Plateau Aquifer

The Springfield Plateau aquifer is the uppermost unit of the Ozark Plateaus aquifer system. It

is much more restricted in areal extent than the lower aquifer units, and the water generally occurs under unconfined conditions. Water in this unit moves west and northwest to discharge areas in the topographic low overlying the transition zone (fig. 13). Concentrations of dissolved solids in water from the aquifer are generally smaller than those in water from the underlying rocks; concentrations in most samples were less than 500 mg/L, and only a few samples contained concentrations of more than 1,000 mg/L (fig. 13).

Water in the Springfield Plateau aquifer is almost everywhere a calcium bicarbonate type. Chloride is a very minor constituent (fig. 14); more than one-half the samples available had chloride concentrations of less than 10 mg/L. Ratios of sodium to chloride are typically about 1.0 (fig. 15).

Calcium-to-magnesium ratios in water from the Springfield Plateau aquifer are generally greater than 5.0 in southwest Missouri and northwest Arkansas and less than 2.0 along the boundary with the Plains subregion (fig. 16). Both the water type and the calcium-to-magnesium ratios reflect the preponderance of calcite over dolomite in the rock matrix of the aquifer and indicate that the water chemistry is the result of interactions between the aquifer materials and meteoric water containing dissolved carbon dioxide.

The Springfield Plateau aquifer is used extensively in the western part of the subregion where it is the major source of domestic water. The very dilute water from this aquifer is satisfactory for most uses.

Shallow Water-Bearing Zone in Pre-Cretaceous Rocks

The Great Plains aquifer system is thin or absent throughout much of the southeastern two-thirds of the study area (fig. 3). Over this broad area, older rocks are at or near the land surface and have been exposed to a long period of erosion and subaerial weathering. Both the hydraulic properties of the rocks and the chemical character of the ground water have been altered by these processes. In many places, the permeability of the rocks has been increased by solution of carbonate and evaporite deposits, and thin confining units have been eroded away. The chemical composition of the

water has been affected by the admixture of large amounts of meteoric water and owes little to the effects of regional circulation patterns or to the composition of original formation water.

Accordingly, the chemistry of the shallow ground water, at depths of less than 500 feet, is illustrated separately, with minimal reference to the regional flow systems.

In the Plains subregion, however, most shallow wells obtain water from the various units of the Western Interior Plains confining system, and water chemistry varies greatly, even over short distances. Some of the more permeable units, such as sandstone of the Douglas Group in eastern Kansas and rocks of equivalent age in eastern Oklahoma, are locally important aquifers. In the Ozark subregion, where the principal aquifers are at or near the land surface, little or no hydrochemical distinction can be made between water from shallow depths and that from the deeper parts of the Ozark Plateaus aquifer system.

The distribution of dissolved-solids concentrations in water from depths of less than 500 feet is shown in figure 30. Where samples from adjacent wells differ greatly in dissolved-solids concentrations, the samples are nearly always from different depths, but there is no consistent relation between concentration and depth of sampling. Composition of the aguifer materials is the predominate factor affecting water chemistry. Larger concentrations of dissolved solids, locally greater than 100,000 mg/L, generally are related to solution of evaporite deposits (halite and gypsum) by ground water of meteoric origin. The subsurface dissolution front of the halite layers extends from Saline County in central Kansas through Beckam County, Oklahoma, adjacent to Texas on the southern boundary of the study area (Gillespie and Hargadine, 1981; Gogel, 1981). Several streams draining land east of the dissolution front (for example, Salt Fork of the Arkansas River in Oklahoma and Rattlesnake Creek in Kansas) have base flow containing dissolved halite from the dissolution zone.

In the Ozark subregion, large concentrations of dissolved solids are most commonly associated with sodium chloride or calcium sulfate type water. Bicarbonate is the predominate anion in most of the more dilute water; calcium is generally the

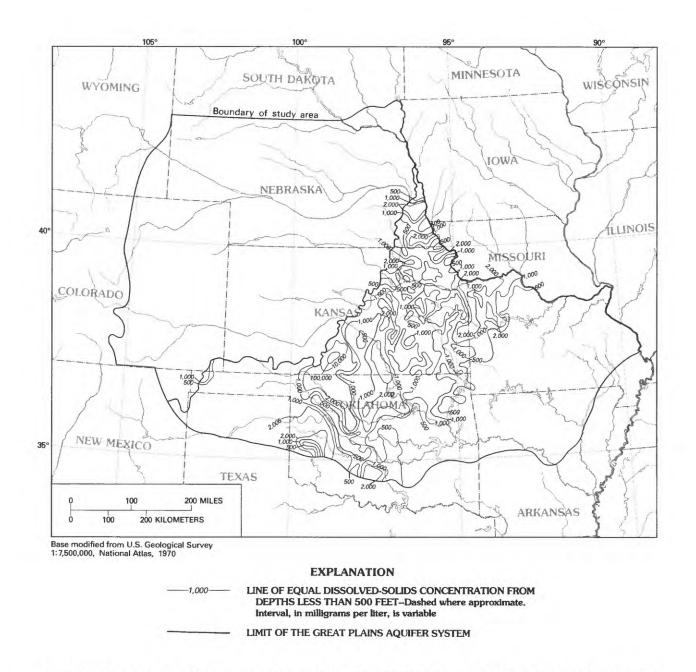


Figure 30. Dissolved-solids concentrations in water from rocks older than those of the Great Plains aquifer system at depths of less than 500 feet.

predominate cation, but sodium bicarbonate water is common in central Oklahoma.

Chloride concentrations are generally less than 100 mg/L in water from shallow wells (fig. 31) although much larger concentrations are found in some wells throughout the study area. Large concentrations of chloride, more than 5,000 mg/L,

in south-central Kansas and in the vicinity of Kansas City are associated with halite deposits at shallow depth.

In most of the area, except the areas of the "Garber-Wellington" aquifer in central Oklahoma, where usable water can be had from the Western Interior Plains confining system, surface-water

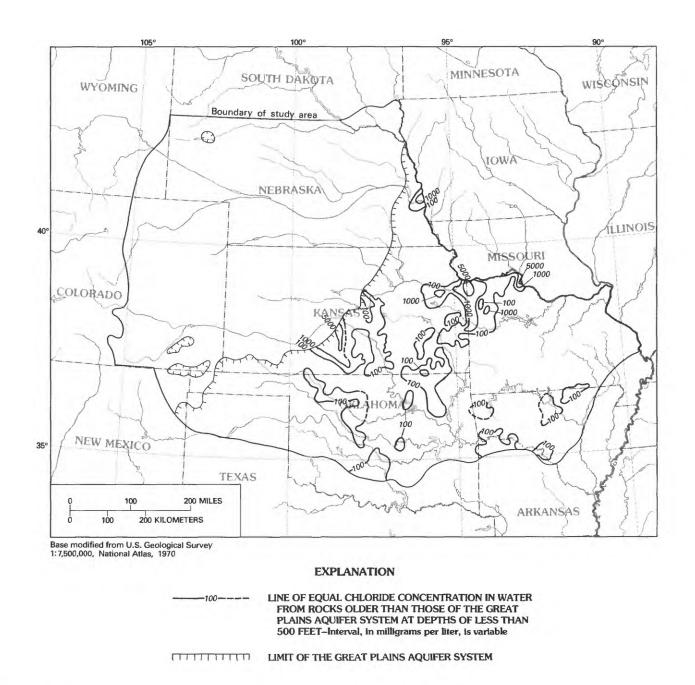


Figure 31. Chloride concentrations in water from rocks older than those of the Great Plains aquifer system at depths of less than 500 feet.

supplies are abundant and reliable; hence there is little demand for ground water. Use of ground water generally is restricted to small-discharge wells for household and livestock use and to a few small public supplies.

SUMMARY

Within the 370,000-square-mile study area of the Central Midwest RASA, rocks ranging in age from Precambrian to Cretaceous contain three regional aquifer systems and three regional confining systems. The basement confining unit, in crystalline rocks of Precambrian age, underlies the entire study area and effectively prevents the downward movement of water. Although a few wells obtain water from fractures in these rocks at shallow depths, the unit as a whole is not considered an aquifer, and the hydrochemistry was not evaluated.

In most of the Interior Plains physiographic province (Plains subregion), rocks of Late Cambrian through Mississippian age comprise the Western Interior Plains aquifer system, which includes lower aquifer units, a confining unit, and an upper aquifer unit.

Water from the lower aquifer units of the Western Interior Plains aquifer system contains less than 10,000 mg/L dissolved solids in only a few areas; locally, in the eastern part of the Anadarko Basin in Oklahoma, dissolved-solids concentrations exceed 300,000 mg/L. Movement of ground water is complex. In the western part of the area, flow is toward the southeast, changing to east-southeast along the Central Kansas Uplift. In the southern part of the lower aquifer units, water moves radially outward from the Anadarko Basin. Virtually all water from these units is a sodium chloride type, with chloride concentrations larger than 150,000 mg/L in the Anadarko Basin. Sodium-to-chloride ratios are generally near that of seawater, and calcium-to-magnesium ratios are commonly about 2.5. Chloride-to-sulfate ratios, however, are typically much larger than that of present-day seawater, suggesting loss of sulfate during the concentration of the original marine water.

The confining unit and upper aquifer unit of the Western Interior Plains aquifer system were removed from large parts of the area by erosion during Mississippian time. Where the units are present, the water is somewhat more dilute than that from the lower aquifer units. The distribution of dissolved-solids concentrations is generally similar, but maximum concentrations are typically less than 250,000 mg/L. Ground-water flow patterns are generally similar to those in the underlying rocks. Nearly all the water is a sodium chloride type, with chloride concentrations locally larger than 150,000 mg/L. Sodium-to-chloride ratios are typically smaller than those in the lower aquifer units, generally ranging from about 0.65 to 0.8. Ratios of calcium to magnesium are larger than

those in the lower aquifer units, reflecting the presence of more limestone and less dolomite in the upper aquifer unit. Chloride-to-sulfate ratios tend to be smaller than those in water from the lower aquifer units but typically much larger than that of seawater.

Brines in the Western Interior Plains aquifer system probably originated as seawater trapped in the rocks at the time of deposition or as evaporative marine brines introduced into the rocks during Permian time. Most of the sulfate ion in the original water was lost, probably by reduction through bacterial action. Extensive dolomitization of the rocks during diagenesis removed magnesium ion and (or) added calcium ion so that the present calcium-to-magnesium ratios are 10 or more times larger than that of present-day seawater.

Although the Western Interior Plains confining system functions as a regional confining unit, the extensive limestone and sandstone units in the lower part of the system are permeable and locally are water bearing or contain prolific oil reservoirs. Water from the system at depths below 500 feet generally contains large concentrations of dissolved solids, locally as large as 300,000 mg/L. Dissolved-solids concentrations tend to vary inversely with depth, probably as a result of the depth below the extensive evaporite deposits in the upper part of the system. Regional movement of ground water through the system appears to be primarily from west to east. Most water samples are a sodium chloride type, and chloride concentrations of 50,000 mg/L or larger are common throughout most of the system. The ratio of sodium to chloride is generally larger than 0.8; locally, ratios of 1.0 or larger probably reflect the dissolution of halite. Ratios of calcium to magnesium are generally in the range of 1.0 to 4.0, and ratios of chloride to sulfate are typically large. Locally, calcium-to-magnesium ratios as large as 10 and chloride-to-sulfate ratios less than 50 probably result from dissolution of gypsum.

In the northwestern part of the study area, the Western Interior Plains confining system is overlain by rocks of Cretaceous age that contain the Great Plains aquifer system. This system consists of two aquifer units, both composed primarily of poorly cemented water-bearing sandstone, separated by a thin and discontinuous shale confining unit. The direction of ground-water flow and the

chemistry of the water are generally similar in both aguifer units. Concentrations of dissolved solids exceed 5,000 mg/L in most water from the interior, more deeply buried, part of the system and are as large as 125,000 mg/L locally in western Nebraska. Water flows generally from west to east through the system. Where the rocks crop out in the northwestern and southwestern corners of the study area, dissolved-solids concentrations of less than 1,000 mg/L are probably the result of recharge entering the exposed rocks. Outside the Denver Basin, large concentrations of dissolved solids seem to be related to evaporite deposits in the underlying confining system. Around the southern and eastern boundaries of the system, the aguifers are at or near land surface, and small concentrations of dissolved solids result from addition of meteoric water or freshwater from overlying aguifers.

Water type in the Great Plains aquifer system varies greatly. The more saline water (more than 5,000 mg/L dissolved solids) is generally a sodium chloride type, but fresher water is a sodium sulfate, sodium bicarbonate, or calcium bicarbonate type. Calcium sulfate water in northeastern Nebraska and in small areas near the eastern boundary of the system in Kansas probably are related to solution of gypsum or to upward leakage of water from the underlying Permian rocks. Chloride concentrations in most parts of the system are considerably less than that of present-day seawater, suggesting that the sediments were deposited in brackish (rather than saline) water or that there has been much flushing and dilution of connate water. Sodium-tochloride ratios in most of the system are larger than that of present-day seawater; near the outcrop areas, sodium-to-chloride ratios as large as 10 suggest the addition of sodium-rich water. Calcium-tomagnesium ratios in most of the aquifer system range from about 0.2 to 3.5 and are associated with a variety of water types and concentrations. Ratios of chloride to sulfate vary considerably and seem to relate generally to chloride concentrations.

Dolostone, limestone, sandstone, and shale of Cambrian through Mississippian age in the Ozark Plateaus physiographic province (Ozark subregion) comprise the Ozark Plateaus aquifer system. These rocks are extensively fractured and faulted and have been exposed repeatedly to long episodes of subaerial weathering and erosion. The carbonate

rocks contain abundant solution openings through which regional ground water moves radially away from a topographic high near the center of the area. The system is divided into three aquifer units separated by two confining units.

The lowermost aquifer unit, the St. Francois aquifer, is separated from the overlying Ozark aquifer by the St. Francois confining unit. The confining unit is generally leaky and locally absent, and the hydrochemistry of the two aquifers is similar. Water in these aquifers commonly contains less than 500 mg/L dissolved solids and is a calcium magnesium carbonate type. Sodium, sulfate, and chloride concentrations in most samples are only a few milligrams per liter. Calcium-to-magnesium ratios are typically about 1.0, consistent with the predominately dolomitic rocks. Overall, the water chemistry represents meteoric water charged with carbon dioxide approaching equilibrium with the carbonate rocks.

The upper aquifer unit, the Springfield Plateau aquifer, is at or near the land surface over much of its extent, and is generally unconfined. As in the underlying aquifers, the chemical character of the water is the result of the solution of aquifer materials by meteoric water. Dissolved-solids concentrations commonly are less than 500 mg/L, and virtually all water samples are a calcium bicarbonate type. Calcium-to-magnesium ratios are generally larger than 5.0, reflecting the preponderance of limestone over dolostone in the rocks of this unit.

In the southeastern two-thirds of the study area, where rocks of the Great Plains aquifer system are thin or absent, the older rocks have been exposed to a long period of erosion and subaerial weathering. Many wells obtain water from rocks of the Western Interior Plains confining system at depths of less than 500 feet. Increased permeability of many of these rocks, due to weathering and solution, together with recharge by meteoric water, have altered the chemical character of the shallow ground water, which now bears little resemblance to the water in deeper, regional flow systems. Solution of the rock materials by meteoric water is the principal factor affecting the chemistry of ground water. Concentrations of dissolved solids range from a few hundred milligrams per liter to more than 100,000 mg/L and vary considerably over short distances, reflecting the variability of the rock materials both laterally and vertically. The more dilute water is generally a calcium bicarbonate type; water with large concentrations of dissolved solids is a sodium chloride or calcium sulfate type and generally associated with the presence of evaporite deposits.

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